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A Demonstration of the Dynamic Tests Developed for NHTSA's NCAP Rollover Rating System

Phase VIII of NHTSA's Light Vehicle Rollover Research Program

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16. Abstract

The work presented in this report focused on testing the dynamic rollover resistance of 14 new vehicles using the maneuvers and procedures developed by NHTSA during previous phases of its Light Vehicle Rollover Research Program. Results from seven sport utility vehicles (SUVs), four pick-ups, and three passenger cars are presented. The vehicles were selected on the basis of their inclusion in the 2004 New Car Assessment Program (NCAP). Three vehicles were equipped with an electronic stability control system (ESC). If the vehicle was equipped with ESC, all tests were performed with the system enabled.

Of the 14 vehicles discussed in this report, two produced two-wheel lift: the Ford Sport Trac 4x2 and the Toyota Tacoma 4x4. Two-wheel lift was observed during Fishhook tests performed with Nominal and Multi-Passenger configurations for the Tacoma 4x4. Only tests performed with the Multi-Passenger load produced two-wheel lift with the Sport Trac 4x2. Note that only the Fishhook test in the heavy multi-passenger load configuration is used by the NCAP rating system.

Use of the Fishhook's supplemental test procedures worked well for the vehicles discussed in this report. In the case of the Toyota Tacoma 4x4 in the light Nominal load configuration, Supplemental Procedure Part #1 tests performed with new tires validated the two-wheel lift that occurred during a Default Procedure test series.

A reduction of handwheel angle magnitude (i.e., changing δ_{ss} = 6.5 to δ_{ss} = 5.5) did not increase tip-up propensity. Of the Phase VIII vehicles discussed in this study, every vehicle that produced two-wheel lift did so when δ_{ss} = 6.5.

As a result of the tests performed in Phase VIII, the 2004 Ford Sport Trac 4x2 and the 2004 Toyota Tacoma 4x4 received NCAP rollover ratings based on a "tip-up" in the dynamic test component of NCAP's statistical model of rollover risk.

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CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9[(Fahrenheit) - 32°C]	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

DISCLAIMER

NOTE REGARDING COMPLIANCE WITH AMERICANS WITH DISABILITIES ACT SECTION 508

For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided for graphical images contained in this report to satisfy Section 508 of the Americans With Disabilities Act (ADA).

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ACKNOWLEDGMENTS

The work documented in this report was a coordinated effort by the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VTRC) and the Transportation Research Center Inc. (TRC) to perform rollover resistance tests with 14 light vehicles. Results from these tests will be incorporated into NHTSA's newly established, and Congressionally mandated, NCAP dynamic rollover resistance rating system.

The authors wish to recognize the outstanding support of our research colleagues. W. Riley Garrott, Pat Boyd, and Mark Heitz contributed to the development and revision of the test procedures used in this study. Larry Jolliff performed the required driving. Greg Stevens, Jim Preston, Michael Brown, and Ian Robbins prepared the vehicles for testing by installing instrumentation and outriggers, and assisted with the many necessary tire changes. Dave Dashner and Leslie Portwood performed post-processing of the test data. Preparation of video data has been the ongoing and coordinated effort of Matt Hostetler, Leslie Portwood, and Chris Adams. Jan Cooper provided administrative support.

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EXECUTIVE SUMMARY

Introduction

The work described in this report has been performed as part of NHTSA's responsibility to fulfill the requirements of Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000." In this legislation, Congress directed NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance test has recently been incorporated into the New Car Assessment Program (NCAP).

As a result of research performed over the past three years, NHTSA has isolated and refined a test maneuver capable of satisfying the requirements mandated by the TREAD Act. Recent efforts began with Phase IV of the Light Vehicle Rollover Research Program [1], where the objectivity and repeatability, performability, discriminatory capability and appearance of reality of eight rollover resistance maneuvers were studied. Of these maneuvers, the NHTSA Fishhook and J-Turn were deemed the most desirable.

Phases VI and VII used the J-Turn and Fishhook[1] maneuvers to evaluate the dynamic rollover resistance of 26 light vehicles [2]. Results from these tests, along with known rollover crash data, were used to develop a logistic regression model to rate relative rollover risk as a function of a vehicle's Static Stability Factor (SSF) and whether a vehicle produced two-wheel lift on the test track [3]. Multiple iterations of the logistic regression model demonstrated that use of multiple maneuvers and load configurations was not advantageous (inclusion of all data had little effect on the overall model), thus allowing a further reduction in the necessary test track maneuvers and vehicle configurations. Ultimately, only Fishhook tests performed in a "Multi-Passenger" configuration were deemed necessary.

Phase VIII tests, discussed in this report, were performed during the second half of 2003. These tests used the most contemporary iteration of NHTSA's Fishhook, i.e., that published on October 14, 2003 in the Federal Resister [3]. Results from these tests will facilitate the calculation and dissemination of NCAP ratings designed to reflect on- and off-road rollover resistance.

Objective

The objective of this testing, Phase VIII of NHTSA's Light Vehicle Rollover Research Program, was to evaluate the dynamic rollover resistance of selected light vehicles using the most recent iteration of the NHTSA Fishhook test procedure. The logistic models used by NHTSA to derive its NCAP rollover ratings require these data. Results presented in this report, combined with measurements of each vehicle's SSF, provide NHTSA with enough data to rate the relative rollover risk of 14 vehicles.

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[1] NHTSA has recently abandon use of the maneuver name "Road Edge Recovery," and has reverted back to the term "Fishhook" to describe the reverse-steer maneuver used to evaluate dynamic rollover resistance.

Test Conditions

Dynamic rollover test results from fourteen vehicles—seven sport utility vehicles (SUVs), four pick-ups, and three passenger cars—are presented in this report. Factors used to select vehicles for NCAP testing included vehicle classification, projected sales volume, and in some instances, because the vehicle was equipped with safety technology of interest to NHTSA. Each vehicle was procured by NHTSA as new. Three vehicles were equipped with electronic stability control systems (ESC), and one of these vehicles also featured Roll Stability Control (RSC). Roll Stability Control can be thought of as an extension of a conventional ESC, but its control logic differs conceptually. While the intent of a conventional ESC (yaw stability control) is to preserve driver controllability and cause the vehicle to follow the drivers intended path as well as road traction allows, RSC endeavors to directly suppress on-road, untripped rollovers; even if that path deviates from the path conventional ESC would have otherwise endeavored to maintain. If the vehicle was equipped with ESC or ESC/RSC, all tests were performed with the systems enabled. This will be standard practice for all future tests performed in support of the rollover NCAP rating system.

The vehicles were tested in two configurations: Nominal Load[2] and Multi-Passenger. The Nominal Load configuration consisted of the driver, instrumentation, programmable steering machine, titanium outriggers, and a full tank of fuel. In addition to the equipment used in the Nominal Load configuration, Multi-Passenger loading used up to three 175 lb water dummies. With two exceptions, these water dummies were positioned in each of the three designated second row seating positions. Since some of the pickups used in this study were designed with only two designated second row seating positions, the third water dummy was secured near the front of the bed in a manner intended to emulate the center seating position of a third seating row. Regardless of the vehicle being considered, water dummies were not installed at any front seat position. This not only included the passenger-side front seat, but the middle seat if the vehicle was equipped with a bench seat.

When completely filled, a water dummy weighs approximately 175 lbs. For some vehicles, use of completely filled water dummies in every designated seating position caused the front and/or rear Gross Axle Weight Rating (GAWR) and/or vehicle Gross Vehicle Weight Rating (GVWR) to be exceeded. To remedy this situation, the weight of each dummy was equally reduced until the GVWR and rear GAWR were no longer exceeded and the front GAWR was not exceeded by more that 50 pounds. To prevent slosh from confounding test outcome, sections of low density Styrofoam were used to uniformly displace the water.

All Phase VIII tests were performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The test surface was paved with an asphalt mix representative of that used on many Ohio highways. All tests were performed on dry pavement. Detailed pavement characteristics provided in Section 2.2.

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[2] It is important to realize that while provided in this report, results from Nominal Load tests should be considered academic (i.e., the model used to calculate NCAP rollover ratings required only results from Multi-Passenger tests).

Test Maneuvers

Each test vehicle was evaluated with one Characterization maneuver (the Slowly Increasing Steer maneuver) and one Rollover Resistance maneuver (the NHTSA Fishhook maneuver). Slowly Increasing Steer data were used to define Fishhook handwheel input magnitudes. A programmable steering machine was used to generate the handwheel steering inputs for each test used in this study. Although most vehicles were evaluated with two load configurations, only results from the Multi-Passenger configuration will be used to calculate the vehicles' NCAP rollover ratings.

Conclusions

Of the fourteen vehicles discussed in this report, two produced two-wheel lift: the Ford Sport Trac 4x2 and the Toyota Tacoma 4x4. Two-wheel lift was observed during Fishhook tests performed with both load configurations for the Tacoma 4x4. Only tests performed with the Multi-Passenger load produced two-wheel lift with the Sport Trac 4x2.

Use of the Fishhook's supplemental test procedures worked well for the vehicles discussed in this report. In the case of the Toyota Tacoma 4x4 in the light Nominal Load configuration, Supplemental Procedure Part #1 tests performed with new tires validated the two-wheel lift that occurred during a Default Procedure test series.

A reduction of handwheel angle magnitude (i.e., changing δ_{ss} = 6.5 to δ_{ss} = 5.5) did not increase tip-up propensity. Of the Phase VIII vehicles discussed in this study, every vehicle that produced two-wheel lift did so when δ_{ss} = 6.5.

As a result of the tests performed in Phase VIII, the 2004 Ford Sport Trac 4x2 and the 2004 Toyota Tacoma 4x4 received NCAP rollover ratings based on a "tip-up" in the dynamic test component of NCAP's statistical model of rollover risk. The statistical risk model is discussed in NHTSA's public notice on NCAP rollover resistance ratings [3].

1.0 INTRODUCTION

The work described in this report has been performed as part of NHTSA's responsibility to fulfill the requirements of Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000." In this legislation, Congress directed NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test has recently been incorporated into the New Car Assessment Program (NCAP).

As a result of research performed over the past three years, NHTSA has isolated and refined a test maneuver capable of satisfying the requirements mandated by the TREAD Act. Recent efforts began with Phase IV of the Light Vehicle Rollover Research Program [1], where the objectivity and repeatability, performability, discriminatory capability and appearance of reality of eight rollover resistance maneuvers were studied. Of these maneuvers, the NHTSA Fishhook and J-Turn were deemed the most desirable.

Phases VI and VII used the J-Turn and Fishhook[3] maneuvers to evaluate the dynamic rollover resistance of 26 light vehicles [2]. Results from these tests, along with known rollover crash data, were used to develop a logistic regression model to rate relative rollover risk as a function of a vehicle's Static Stability Factor (SSF) and whether a vehicle produced two-wheel lift on the test track [3]. Multiple iterations of the logistic regression model demonstrated that use of multiple maneuvers and load configurations was not necessary (inclusion of all data had little effect on the overall model), thus allowing a further reduction in the test track maneuvers and vehicle configurations. Ultimately, only Fishhook tests performed in a "Multi-Passenger" configuration were deemed necessary.

Phase VIII tests, discussed in this report, were performed during the second half of 2003. These tests used the most contemporary iteration of NHTSA's Fishhook, i.e., that published on October 14, 2003 in the Federal Resister [3]. Results from these tests will facilitate the calculation and dissemination of NCAP ratings designed to reflect untripped and tripped rollover resistance.

Structure of This Report

Chapter 1 has briefly introduced the mandate of the TREAD Act and outlined the testing NHTSA has performed in response to it. Chapter 2 explains the objectives and the overall methodology used for the work presented in this report. Chapter 3 describes the test vehicles, discusses the vehicle configurations, tires, and outriggers used for this research. Chapter 4 describes the instrumentation and data acquisition systems that were installed in each test vehicle.

Chapter 5 discusses the two maneuvers used in this study (the Slowly Increasing Steer and NHTSA Fishhook). This chapter includes maneuver descriptions and presents the Fishhook handwheel steering angles used for each vehicle.

[3]NHTSA has recently abandon use of the maneuver name "Road Edge Recovery," and has reverted back to the term "Fishhook" to describe the reverse-steer maneuver used to evaluate dynamic rollover resistance.

Chapter 6 is an assessment of the ability of the steering machine (used for all steering inputs in this study) to achieve the commanded handwheel angles and rates.

Chapter 7 presents Fishhook maneuver test results. The occurrences of two-wheel lift, and the maneuver entrance speeds required to produce it, are presented.

Chapter 8 gives the overall conclusions from the Fishhook tests conducted.

2.0 OBJECTIVES

2.1 Work Performed During Phase VIII of the Rollover Research Program

Phase VIII testing was performed during the second half of 2003. The objective of this work was to evaluate the dynamic rollover resistance of selected light vehicles. Results from these tests will facilitate the calculation and dissemination of NCAP ratings designed to reflect rollover risk in the event of a single vehicle crash – the circumstance of over 80 percent of rollovers.

2.1.1 Vehicles Tested

Dynamic rollover test results from 14 vehicles—seven sport utility vehicles (SUVs), four pick-ups, and three passenger cars—are presented in this report. Each vehicle was new. A detailed description of the test vehicles used in this study is provided in Chapter 3.

2.1.2 Load Configurations

Most vehicles were tested in two configurations: Nominal Load and Multi-Passenger. A detailed description of these configurations is provided in Chapter 3. Note that only the tests in the Multi-Passenger configuration were used for NCAP ratings. The Nominal Load tests were continued as a contingency during the development of the statistical model for rollover risk.

2.1.3 Maneuvers Examined

Each test vehicle was evaluated with one Characterization maneuver (the Slowly Increasing Steer) and one Rollover Resistance maneuver (the NHTSA Fishhook). Slowly Increasing Steer test results were used to define Fishhook handwheel input magnitudes. A programmable steering machine was used to generate the handwheel steering inputs for each test used in this study. Brief maneuver descriptions are as follows.

> **Slowly Increasing Steer.** This maneuver requires the steering wheel be turned slowly to a desired magnitude while the driver attempts to maintain a constant speed. Although Slowly Increasing Steer tests can be used to provide important handling information, NHTSA's Rollover Resistance tests only require data output from this maneuver to define handwheel input magnitudes.
>
> **NHTSA Fishhook.** The NHTSA Fishhook maneuver is identical to the Phase IV Fishhook 1b maneuver. The maximum handwheel steering angle magnitude was equal to 6.5 times the handwheel angle at which 0.3 g lateral acceleration was attained during Slowly Increasing Steer tests performed with the same vehicle and vehicle load configuration. Like Fishhook 1b, the countersteer magnitude was equivalent to the maximum initial steer, and roll rate feedback is used to determine handwheel reversal timing.

More complete details of the Slowly Increasing Steer and Fishhook maneuvers are provided in Chapter 5. Results from the Fishhook maneuvers are provided in Chapters 6 and 7.

2.1.4 Phase VIII Test Sequence

Each Phase VIII test vehicle was evaluated with multiple maneuver and, in most cases[4], multiple load configuration combinations. Although the specific details pertaining to test conduct are provided in Chapters 3 and 5, Figure 2.3 outlines the overall testing progression typically used for each vehicle. Future tests used will include Nominal Load tests only if no Multi-Passenger Configuration exists for the vehicle being evaluated (e.g., a two-seat sports car). Generally speaking, a vehicle's NCAP rollover rating will include contributions from Fishhook Tests performed in the Multi-Passenger Configuration only.

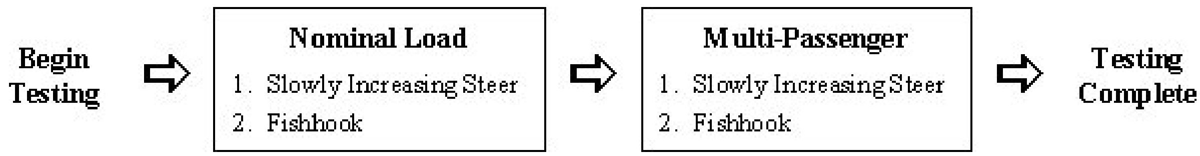

Figure 2.3. Overall Phase VIII Test Sequence.

2.1.5 Metrics Measured For Each Vehicle

Unlike the work performed during NHTSA's previous rollover research phases, the focus of Phase VIII testing was very narrow. The work presented in this report was performed only to support the determination of NCAP rollover resistance ratings of fourteen vehicles and to provide a final opportunity to evaluate procedure/methodology. For this reason, only three major items were ultimately required for each vehicle:

1. The overall handwheel position at 0.3 g in the Multi-Passenger [or Nominal Load[5]] Configuration.
2. Two-Wheel Lift during the NHTSA Fishhook maneuver in the Multi-Passenger [or Nominal Load[5]] Configuration (Yes/No).
3. Rim-to-Pavement Contact or Tire Debeading during the NHTSA Fishhook maneuver in the Multi-Passenger [or Nominal Load[5]] Configuration (Yes/No).

While provided in this report, results from Nominal Load are not used for generating the vehicle's rollover resistance ratings (i.e., the logistic regression models used to calculate NCAP rollover ratings relied only the results from Multi-Passenger tests).

2.2 Test Surface

[4]Tests were performed with the 2003 Toyota Echo and 2004 Chevrolet Trailblazer 4x2 and 4x4 after the decision to only incorporate results from the Multi-Passenger configuration into the NCAP rollover rating system. Since results from Nominal Load tests were not necessary, these tests were not performed.

[5]Nominal Load tests results are only used if no Multi-Passenger Configuration exists for the vehicle being evaluated (e.g., a 2-seat sports car).

All Phase VIII tests were performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The VDA is an 1800 by 1200 foot flat paved surface with a one percent longitudinal grade for drainage. Turn-around loops are provided on each end to facilitate high speed entry onto the VDA. The surface was paved with an asphalt mix representative of that used on many Ohio highways. All Phase VIII tests were performed on dry pavement.

The VDA's peak and sliding coefficients of friction were generally monitored twice per month, weather-permitting, using American Society for Testing and Materials (ASTM) procedures. The peak coefficient was determined with ASTM procedure E1337 and an E1136 tire [4,5]. Sliding coefficients were determined with ASTM procedure E274 and an E501 tire [6,7]. Table 2.2 summarizes the available results for the 2003 calendar year.

Table 2.2. Peak and Slide Coefficients of Friction During Calendar Year 2003 for the TRC VDA.

Date	Coefficient Of Friction	
	Peak	Sliding
01.09.2003	Not Available	0.89
01.22.2003	Not Available	Not Available
02.03.2003	Not Available	Not Available
03.04.2003	0.97	Not Available
03.25.2003	0.95	0.85
04.07.2003	0.96	0.88
04.28.2003	0.96	0.85
05.12.2003	0.98	0.86
05.27.2003	0.98	0.80
06.10.2003	0.89	0.86
06.27.2003	0.96	0.87
07.18.2003	0.94	0.86
07.31.2003	0.98	0.88
08.18.2003	0.94	0.87
09.02.2003	0.98	0.85
09.15.2003	0.97	0.83
09.29.2003	0.96	0.83
10.17.2003	0.97	0.82
11.03.2003	0.92	0.88
11.17.2003	0.96	0.86

3.0 TEST VEHICLES AND CONFIGURATIONS

3.1 Vehicle Selection Rationale

Dynamic rollover tests results from fourteen vehicles—seven sport utility vehicles (SUVs), four pick-ups, and three passenger cars—are presented in this report. Factors used to select the vehicles included vehicle classification, projected sales volume, and in some instances, because the vehicle was equipped with safety technology of interest to NHTSA as standard equipment. Each vehicle was procured new by NHTSA. Three vehicles were equipped with an electronic stability control system (ESC). If the vehicle was equipped with ESC, all tests were performed with the system enabled.

Table 3.1 provides several descriptive parameters for each test vehicle. These parameters are not intended to be comprehensive descriptions of each vehicle, but to highlight certain features the authors deem relevant to rollover propensity and vehicle loading. This table presents baseline test weights and SSF measurements. Used here, the term "baseline" refers to the state of the vehicle as received from the dealer, albeit with a 50th percentile male driver and full tank of fuel. The effects of outrigger installation, instrumentation, etc. are not represented in Table 3.1; rather they are discussed in a later section of this chapter. Appendix Table A.1 summarizes the baseline static stability factors and pitch, roll, and yaw inertia measurements of the Phase VIII test vehicles discussed in this report.

3.2 Electronic Stability Control

Three vehicles were equipped with electronic stability control systems (ESC) as standard equipment. In the case of the two Toyota 4Runners, the system is referred to as Vehicle Skid Control, or "VSC." Toyota has installed VSC as standard equipment on all Toyota 4Runners sold in the United States since model year 2001. In the case of the Volvo XC90, the system is referred to as Dynamic Stability Traction Control, or "DSTC." Unlike the system used on the 4Runner, the XC90 also includes Roll Stability Control, or "RSC." Roll Stability Control can be thought of as an extension of a conventional ESC, but its control logic differs conceptually. While the intent of a conventional ESC (yaw stability control) is to preserve driver controllability and cause the vehicle to follow the drivers intended path as well as road traction allows, RSC endeavors to directly suppress on-road, untripped rollovers. This is accomplished via direct measurement of the vehicle's roll motion (an operation not typically performed by an ESC system) and outside front brake application aggressive enough to change the vehicle's path to relieve lateral acceleration—even if that path deviates from the path conventional ESC would have otherwise endeavored to maintain.

3.3 Tires

3.3.1 Description

The tires used for each vehicle were new, and of the same make, model, size, load rating, and speed rating as installed by the manufacturer as original equipment (OE). Additionally, at least the third through seventh DOT numbers/letters of the tires used during Phase VIII tests were the same as the OE tires. All test tires were inflated to the pressures recommended by each manufacturer on the vehicle identification placards. Appendix Table A.2 presents the tire information for each Phase VIII vehicle.

3.3.2 Break-In Procedure

Prior to actual testing, the tires were "scrubbed in" to wear away mold sheen and be brought up to operating temperature. This was accomplished by driving the vehicle around a circle 100 feet in diameter at a speed that produced a lateral acceleration of approximately 0.5 to 0.6 g. Using this circle, three clockwise laps were followed by three counterclockwise laps. Once these six laps were complete, the driver input sinusoidal steering using a handwheel angle capable of producing a lateral acceleration of 0.5 to 0.6 g (δ_{ss}) at a frequency of 1 Hz for 10 cycles while maintaining a vehicle speed of 35 mph. A total of four passes using sinusoidal steering were used. The handwheel magnitude of the final cycle of the final pass was twice that of δ_{ss}. A programmable steering machine was used to input all sinusoidal steering used during the break-in procedure.

Table 3.1. Test Vehicle Descriptive Parameters (Baseline Condition, Sorted By Static Stability Factor In Descending Order, Per Vehicle Class).

Vehicle			Engine	GVWR (lbs)	Rear GAWR (lbs)	Miscellaneous Features	Wheelbase (in)	Mean Track Width (in)	Test Weight w/o outriggers (lbs)	Steering Ratio (deg/deg)	SSF
Description	Model Year	Make/Model									
SUV	2004	Volvo XC90[1]	2.5L I5 Turbo	6005	3240	4-dr, AWD, 5-spd auto, DSTC, RSC	112.3	64.2	4803.5[1]	15.95	1.209[1]
SUV	2004	Chevrolet Trailblazer 4x4	4.2L I6	5750	3200	4-dr, 4WD, 4-spd auto	113.3	62.4	4702.4	19.91	1.187
SUV	2004	Chevrolet Trailblazer 4x2	4.2L I6	5550	3200	4-dr, RWD, 4-spd auto	113.2	62.4	4516.2	20.44	1.166
SUV	2003	Toyota 4Runner 4x4	4.0L V6	5380	2935	4-dr, 4WD, 4-spd auto, VSC	109.9	62.2	4408.8	17.28	1.165
SUV	2003	Toyota 4Runner 4x2	4.0L V6	5120	2900	4-dr, RWD, 4-spd auto, VSC	109.9	62.2	4162.1	17.48	1.150
SUV	2003	Jeep Liberty 4x4	3.7L V6	5600	3150	4-dr, 4WD, 4-spd auto	104.0	60.0	4113.0	18.28	1.149
SUV	2003	Jeep Liberty 4x2	3.7L V6	5350	3150	4-dr, RWD, 4-spd auto	104.0	60.1	3942.2	18.55	1.123
Pick-up	2003	Chevrolet Silverado 4x2	5.3L V8	6400	3686	RWD, 4-spd auto, extended cab, standard bed	143.9	65.6	4761.4	17.86	1.251
Pick-up	2003	Chevrolet Silverado 4x4	5.3L V8	6400	3750	4WD, 4-spd auto, extended cab, standard bed	144.0	65.6	5091.1	16.84	1.198
Pick-up	2003	Toyota Tacoma 4x4	2.7L I4	5100	2800	4WD, 4-spd auto, extended cab, standard bed	122.6	59.1	3833.9	20.48	1.123
Pick-up	2003	Ford Explorer SportTrac 4x2	4.0L V6	5660	3200	RWD, 5-spd auto	125.9	56.4	4298.4	18.32	1.067
Passenger Car	2003	Ford Focus	2.0L T4	3715	1830	4-dr wagon, FWD, 4-spd auto	102.9	58.2	2914.8	15.66	1.295
Passenger Car	2003	Toyota Echo[2]	1.5L T4	2995	1450	4-dr, FWD, 4-spd auto	93.25	56.3	2359.9	18.54	1.282
Passenger Car	2003	Subaru Outback	2.5L H4	4555	2345	4-dr wagon, AWD, 4-spd auto	104.4	58.1	3651.0	20.22	1.264

[1]Logistic complications prevented certain baseline data from being collected. For this reason, measurements of a 2004 Volvo XC90 very similar to the vehicle actually used for the dynamic tests discussed in this study are presented in Table 3.1.

[2]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

3.3.3 Mounting Technique

No lubricant was used when mounting tires to the rims used for testing. This was done to eliminate the possibility of tire lubricant contributing to debeading.

3.3.4 Frequency of Changes

To minimize the effects of tire wear on vehicle response and rollover propensity, frequent tire changes were utilized. With one exception[6], the following guidelines were followed:

- One set of tires was used for each Slowly Increasing Steer test series. Each series was performed with only one load configuration (i.e., Nominal Load and Multi-Passenger Configuration tests were each performed with unique tire sets).

- Each Fishhook test series was performed with the same tire set as those used for the corresponding Slowly Increasing tests (i.e., those performed with the same load configuration). Each series was comprised of left-right and right-left steer tests.

- As explained in Chapter 5, the NHTSA Fishhook test procedure is comprised of four components: the Default Procedure and Supplement Procedure Parts 1, 2, and 3. If two-wheel lift was observed during Fishhook tests performed during execution of the Default Procedure, and the maneuver entrance speed (MES) was ≥47.5 mph, the tire set was replaced with new and the test repeated to assess whether tire wear had potentially confounded the test results. This criteria was also used if two-wheel lift was observed during execution of Supplement Procedure Parts 1, 2, and 3.

3.3.5 Use of Inner Tubes

Fishhook maneuvers have been shown to produce debeading of the outside front and rear tires. The occurrence of debeads can result in significant damage to the test surface [1]. NHTSA research has concluded that the easiest, most cost effective way to minimize debeading is the use of inner tubes designed for radial tires. For this reason, inner tubes were installed prior to the conduct of all Phase VIII Fishhook tests – one inner tube for each of the vehicle's tires. Inner tubes were appropriately sized for the test vehicle's tires.

NHTSA has never observed debeading or rim-to-pavement contact during the conduct of Slowly Increasing Steer tests. For this reason, the authors do not believe installation of inner tubes is necessary for Slowly Increasing Steer tests, regardless of vehicle or load condition. That said,

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[6]The first vehicle to be evaluated in Phase VIII, the 2003 Toyota 4Runner 4x2, used a different tire change criteria than that used for the other vehicles. For this vehicle, each Slowly Increasing Steer test series (Nominal Load and Multi-Passenger configuration tests) used a unique tire set that was not used during later Fishhook tests performed with the same load configuration. In the case of the 4Runner 4x2, a total of four tire sets were used. Had the tire change used for the other vehicles been used, only two sets would have been needed. The authors do not believe the additional tire changes used for this vehicle had any effect on test outcome, just the cost of performing the tests.

the most current Fishhook test procedure (described in Chapter 5 and in [3]) specifies that the Slowly Increasing Steer tests and some Fishhook tests may use the same tire set. For the sake of convenience, it is therefore desirable to install inner tubes prior to Slowly Increasing Steer tests to minimize disruption between conclusion of Slowly Increasing Steer testing and the beginning of the Fishhook maneuver.

3.4 Vehicle Load Configurations

As previously mentioned in Section 2.1.2, tests performed in Phase VIII used two loading configurations: Nominal Load and Multi-Passenger. Table 3.4, presented at the end of this section, compares baseline SSF and pitch, roll, and yaw inertia measurements of each vehicle to those measured in the two load configurations. All values presented in this table are expressed as percentages.

3.4.1 Nominal Load

The Nominal Load configuration consisted of the driver, instrumentation, programmable steering machine, titanium outriggers, and a full tank of fuel. Weight and location specifications for the data acquisition system and steering machine are presented in Table 3.2.

Table 3.2. Equipment Location and Weight.

Equipment	Location	Weight, typical (lbs)
Data Acquisition System	Front passenger seat	58
Steering Machine	Handwheel	31
Steering Machine Electronics Box	Second row foot well, typically behind front passenger seat[1].	39

[1]Vehicles with only front designated seating positions may require the Steering Machine Electronics Box to be placed in the front passenger-side foot well.

To quantify the influence of the Nominal Load on SSF and mass moments of inertia, each vehicle was tested on the Vehicle Inertia Measurement Facility (VIMF) at SEA, Inc (see Appendix Table A.2). Results from tests performed in the Nominal Load configuration were compared with those measured in the baseline condition. Table 3.4 (presented at the end of Section 3.4) summarizes these data. The Nominal Load data presented in this table includes the effects of instrumentation.

The Nominal Load configuration increased the SSF (i.e., lowered the center of gravity) and each mass moment of inertia of every Phase VI test vehicle. The SSFs increased 0.9 percent (Chevrolet Silverado 4x4) to 4.3 percent (Toyota Echo), and averaged 2.5 percent overall.

Increases in pitch inertia ranged from 9.3 percent (Chevrolet Trailblazer 4x2) to 19.9 percent (Toyota Echo), averaging 13.4 percent overall. Roll inertia increased 7.9 percent (Chevrolet Silverado 4x2) to 21.0 percent (Toyota Echo), and averaged 12.0 percent overall. Yaw inertia increased 9.6 percent (Chevrolet Silverado 4x4) to 21.6 percent (Toyota Echo), averaging 14.3 percent overall.

3.4.2 Multi-Passenger

In addition to the equipment used with the Nominal Load configuration, Multi-Passenger loading used three 175 lb water dummies. With two exceptions, these water dummies were positioned in each of the three designated second row seating positions, as shown in Figures 3.1 and 3.2. Since the Toyota Tacoma 4x4 pickup used in this study was designed with only two designated second row seating positions, the third water dummy was secured near the front of the bed in a manner intended to emulate the center seating position of a third seating row.

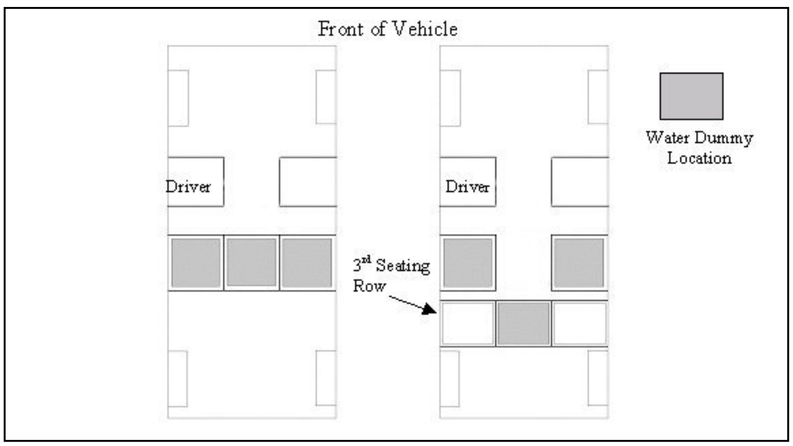


Figure 3.1. Water dummy placement for vehicles with three or more designated rear seating positions, excluding pick-up trucks. **Note:** A water dummy is placed in the third seating row only when the second seating row is limited to two designated seating positions.

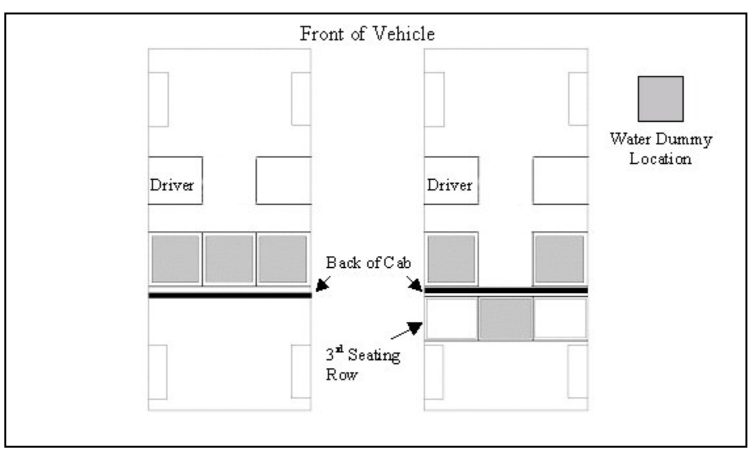


Figure 3.2. Water dummy placement for pick-up trucks with two or more designated rear seating positions. **Note:** A water dummy is placed in a simulated third seating row only when the second seating row is limited to two designated seating positions

Regardless of the vehicle being considered, water dummies were not installed at any front seat position. This not only included the passenger-side front seat, but the middle seat if the vehicle was equipped with a bench seat. Additional information about manner in which the Multi-Passenger configuration is achieved is available in [3].

When completely filled, a water dummy weighs 175 lbs. Table 3.3 provides a summary of the longitudinal and vertical center of gravity (C.G.) positions and mass moments of inertia for a completely filled water dummy. The C.G. values were calculated using geometric approximations of each water dummy (two rectangle boxes). The mass moments of inertia were measured directly at SEA, Inc. on their Small Parts Inertia Tester.

Table 3.3. Water Dummy Calculated / Measured Parameters.

Measurement	Completely Full
Weight	175.0 lbs
Longitudinal C.G. Location (fore of seat back)	7.75 inches
Lateral C.G. Location	Centerline of Dummy
Vertical C.G. Height (above seat)	11.0 inches
Roll Moment of Inertia About C.G.	3.10 ft-lb-s^2
Pitch Moment of Inertia About C.G.	2.99 ft-lb-s^2
Yaw Moment of Inertia About C.G.	1.74 ft-lb-s^2

For some vehicles, use of completely filled water dummies in every designated seating position caused the front and/or rear Gross Axle Weight Rating (GAWR) and/or vehicle Gross Vehicle Weight Rating (GVWR) to be exceeded. To remedy this situation, the weight of each dummy was equally reduced until the GVWR and rear GAWR were no longer exceeded and the front GAWR was not exceeded by more that 50 pounds. In the case of the Ford Focus, the weight of the three water dummies was reduced to 139 lbs to satisfy the previously mentioned load criteria. Similarly, the weights of each dummy used during Subaru Outback and Toyota Echo tests were reduced to 100 lbs and 96 lbs, respectively. To prevent slosh from confounding test outcome when partially filled water dummies were used, sections of low density Styrofoam were used to uniformly displace the water.

Appendix Table A.4 summarizes the Multi-Passenger VIMF data. Table 3.4 compares these data to those collected in the baseline condition. For each of the passenger cars, the Multi-Passenger configuration increased the respective SSFs (i.e., the center of gravity height became lower). The increases in SSF ranged from a 1.8 percent (Subaru Outback) to a 3.0 percent (Toyota Echo), and averaged 2.5 percent overall for these vehicles. With the exception of the Jeep Liberty 4x2, this was not the case for the light trucks and sport utility vehicles used in this study.

For these vehicles, the Multi Passenger configuration generally decreased the respective SSFs (i.e., the center of gravity height was raised). Whereas the Multi-Passenger configuration increased the SSF of the Liberty 4x2 slightly (0.5 percent), the SSFs of the other light trucks and sport utility vehicles decreased from 0.1 percent (Chevrolet Trailblazer 4x2) to 1.8 percent (Chevrolet Silverado 4x4 and Toyota Tacoma 4x4), and averaged 1.1 percent overall.

Increases in pitch inertia ranged from 11.7 percent (Chevrolet Silverado 4x4) to 29.2 percent (Toyota Echo), averaging 19.8 percent overall. Roll inertia increased 13.1 percent (Chevrolet Silverado 4x2) to 26.8 percent (Toyota Tacoma 4x2), and averaged 18.3 percent overall. Yaw inertia increased 11.9 percent (Chevrolet Silverado 4x4) to 30.5 percent (Toyota Echo), averaging 20.0 percent overall.

Table 3.4. Percent Change from Baseline Condition (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	SSF		Pitch Inertia		Roll Inertia		Yaw Inertia	
	Nominal Load	Multi-Passenger	Nominal Load	Multi-Passenger	Nominal Load	Multi-Passenger	Nominal Load	Multi-Passenger
2004 Volvo XC90[1]	1.3	-1.2	N/A	N/A	N/A	N/A	N/A	N/A
2004 Chevrolet Trailblazer 4x4	1.9	-0.4	9.3	16.7	10.2	16.6	10.4	17.1
2004 Chevrolet Trailblazer 4x2	2.4	-0.1	10.5	17.2	10.0	15.4	11.2	17.5
2003 Toyota 4Runner 4x4	2.2	-1.0	13.2	21.0	13.3	20.3	14.0	20.2
2003 Toyota 4Runner 4x2	2.1	-0.8	13.0	19.7	11.4	16.6	13.5	19.3
2003 Jeep Liberty 4x4	2.7	-0.2	15.5	24.3	8.5	17.3	16.9	24.6
2003 Jeep Liberty 4x2	3.3	0.5	16.1	24.1	11.0	17.0	17.2	24.4
2003 Chevrolet Silverado 4x2	1.8	-1.4	10.3	12.7	7.9	13.1	10.4	12.2
2003 Chevrolet Silverado 4x4	0.9	-1.8	9.4	11.7	9.4	14.4	9.6	11.9
2003 Toyota Tacoma 4x4	2.3	-1.8	12.9	19.3	16.1	26.5	14.2	19.2
2003 Ford Explorer SportTrac 4x2	1.8	-1.5	10.2	13.4	11.2	18.2	10.6	14.3
2003 Ford Focus Wagon	3.6	2.7	19.7	28.5	14.4	21.0	21.1	29.2
2003 Toyota Echo[2]	4.3	3.0	19.9	29.2	21.0	24.8	21.6	30.5
2003 Subaru Outback	2.6	1.8	14.6	19.1	12.1	16.1	15.5	19.8

[1]Calculations based on comparison of a 2004 Volvo XC90 very similar to the vehicle actually used in this study (i.e., the values presented in Appendix Table A.1) with the data presented in Appendix Tables A.3 and A.4.

[2]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

3.5 Installation of Outriggers

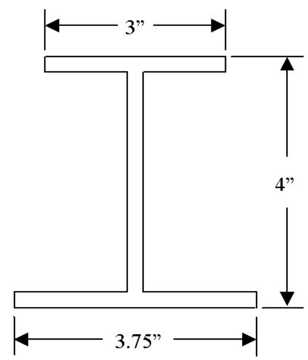
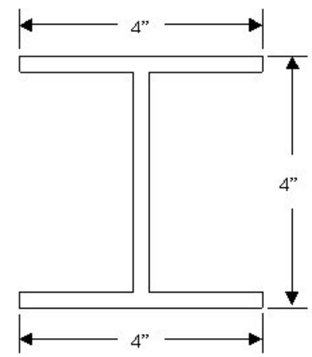
Both vehicle load configurations included instrumentation, a steering machine, and outriggers. Test vehicle bumper assemblies were removed for outrigger installation. The reduction in vehicle weight due to the removal of the bumpers is offset by the additional weight of the outriggers and their mounting system. The outrigger system typically outweighs the bumper assemblies.

The outriggers used in Phase VIII were designed to minimize the effect of their installation on test vehicle roll inertia. Each beam was CNC machined from extruded 6AL-4V titanium I-beams. A typical installation is shown in Figure 3.3.

Figure 3.3. Typical installation of NHTSA's "standard" titanium outriggers.

The outriggers were attached to the front and rear bumper attachment points with steel brackets. Depending on the weight of the vehicle, one of two outrigger designs was used. If a test vehicle weighed less than 3500 lbs in the baseline condition, the “short” outriggers were used. If the test vehicle weighed greater than or equal to 3500 lbs in the baseline condition, the “standard” outriggers were used. Table 3.5 compares the length, weight, cross-sections, and mass moments of inertia of the short and standard outriggers, and shows which outrigger was installed on each test vehicle. Detailed schematics of these outriggers are available in [8].

Table 3.5. Phase VIII Outrigger Specifications and Installation Summary.

Description	Short	Standard
Length	135 inches	147 inches
Flange/Web Thickness	0.25 inches	0.25 inches
Weight	57.5 lbs	63.3 lbs
Cross-section		
Moment of Inertia About Pitch Axis (Through Outrigger C.G.)	≈ 0	≈ 0
Moment of Inertia About Roll and Yaw Axes (Through Outrigger C.G.)	19.6 ft-lb-s^2	24.2 ft-lb-s^2
Vertical C.G. Location	2.2 inches (below top of the top flange)	2.4 inches (below top of the top flange)
Installation Summary	2003 Focus Wagon 2003 Subaru Outback 2003 Toyota Echo	2003 Toyota 4Runner 4x2 2003 Toyota 4Runner 4x4 2003 Jeep Liberty 4x2 2003 Jeep Liberty 4x4 2004 Chevrolet Trailblazer 4x2 2004 Chevrolet Trailblazer 4x4 2004 Volvo XC90 2003 Chevrolet Silverado 4x2 2003 Chevrolet Silverado 4x4 2003 Toyota Tacoma 4x4 2003 Ford Explorer Sport Trac 4x2

4.0 INSTRUMENTATION

Each Phase VIII test vehicle was similarly instrumented with sensors, a data acquisition system, and a programmable steering machine. This chapter briefly describes the test equipment, and how it was utilized.

4.1 Sensors and Sensor Locations

Table 4.1 describes the sensors used to measure vehicle responses. Sensors are listed with the data channel measured in the first column of the table. Additional columns list the sensor type, sensor range, sensor manufacturer, and sensor model number.

Table 4.1. Test Vehicle Sensor Information.

Data Measured	Type	Range	Manufacturer	Model Number
Handwheel Angle	Angle Encoder	Infinite	Automotive Testing, Inc.	Integral with ATI Steering Machine
Brake Pedal Force	Load Cell	0-300 lbf	GSE Inc.	4351
Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Multi-Axis Inertial Sensing System	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	BEI Technologies, Inc. Systron Donner Inertial Division	MotionPak Multi-Axis Inertial Sensing System MP-1
Left and Right Side Vehicle Ride Height	Ultrasonic Distance Measuring System	4-40 inches	Massa Products Corp.	M-5000 / 220 kHz
Vehicle Speed	Radar Speed Sensor	0.1-125 mph	B+S Software und Messtechnik GmbH	DRS-6
Wheel Lift (via resolution of two measured distances spaced a known distance apart)	Analog Displacement Measuring System (Infrared; 880nm)	13.78 - 33.46 inches	Wenglor Sensors Ltd.	HT 66MGV80

Handwheel position was recorded with an angle encoder integral with the programmable steering machine.

Brake pedal force was measured with a load cell transducer attached to the face of the brake pedal. While brake pedal force was not explicitly required by any test performed in Phase VIII, it was important to monitor the driver's braking activity during testing. If the driver applied force to the brake pedal during the conduct of any test, the test was invalid.

A multi-axis inertial sensing system was used to measure accelerations and roll, pitch, and yaw angular rates. The system was placed near the vehicle's C.G. so as to minimize roll, pitch, and yaw effects. Since it was not possible to position the accelerometers precisely at every vehicle's C.G. for each loading condition, sensor outputs were corrected to translate the motion of the vehicle at the measured location to that which occurred at the actual C.G. during post-processing of the data. The equations used for these corrections were derived from equations of general relative acceleration for a translating reference frame and use the SAE Convention for Vehicle Dynamics Coordinate Systems. The sensing system did not provide inertial stabilization of its accelerometers. Therefore, lateral acceleration was also corrected for vehicle roll angle during post processing using the techniques explained in [1].

An ultrasonic distance measurement system was used to collect left and right side vehicle ride heights for the purpose of calculating vehicle roll angle. One ultrasonic ranging module was mounted on each side of a vehicle and were positioned at each vehicle's longitudinal center of gravity. Vehicle roll angle was computed from the output of the two sensors and the roll rate was measured by the multi-axis inertial sensing system. Reference [1] presents the technique used.

Vehicle speed was measured with a non-contact speed sensor placed at the center rear of each vehicle. Sensor outputs were transmitted not only to the data acquisition system, but also to a dashboard display unit. This allowed the driver to accurately monitor vehicle speed.

Wheel lift was measured individually with two height sensors attached to spindles installed at the wheel, as shown in Figure 4.1. Using basic trigonometry, the output of the two sensors was used to resolve the camber angle of the wheel, and remove its influence from the uncorrected height sensor output. A detailed description of how these sensors are calibrated and installed is available in [9].

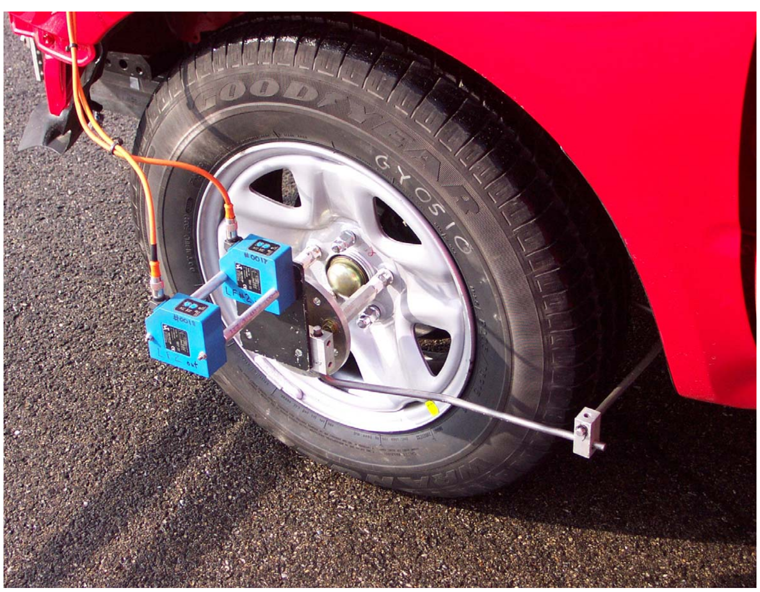


Figure 4.1. Height sensors used to measure wheel lift.

4.2 Programmable Steering Machine

A programmable steering machine produced by Automotive Testing, Inc. (ATI) was used to provide steering inputs for all Phase VI test maneuvers. Descriptions of the steering machine, including features and technical specifications, have been previously documented and are available in [10,11].

The steering machine was configured to reverse the direction of steer close to maximum roll angle during Fishhook maneuvers. This was accomplished by monitoring roll rate zero crossings (i.e., when roll rate goes to zero, roll angle is at a maximum, since roll rate is the derivative of roll angle). Specifically, a roll rate window comparator set to ∀ 1.5 degrees per second was used to command handwheel reversals. When counterclockwise steering is performed, the vehicle rolls in the clockwise direction. As maximum roll angle is achieved, roll rate approaches zero by first passing through the +1.5 deg/sec threshold of the window comparator, thereby commanding a clockwise handwheel reversal. Conversely, when clockwise steering is performed, the vehicle rolls in a counterclockwise direction. As maximum roll angle is achieved, roll rate approaches zero by first passing through the -1.5 deg/sec threshold of the window comparator, thereby commanding a counterclockwise handwheel reversal.

4.3 Data Acquisition

In-vehicle data acquisition systems, comprised of ruggedized industrial computers, recorded outputs from the previously mentioned sensors during the conduct of test maneuvers. All data was sampled at a rate of 200 Hz.

The computers employed the DAS-64 data acquisition software developed by the NHTSA's VRTC. Analog Devices Inc. 3B series signal conditioners were used to condition data signals from all transducers listed in Table 4.1. Measurement Computing Corporation PCI-DAS6402/16 boards digitized analog signals at a collective rate of 200 kHz. Test drivers initiated data collection prior to the start of maneuvers performed with the steering machine.

Signal conditioning consisted of amplification, anti-alias filtering, and digitizing. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Filtering was performed with two-pole low-pass Butterworth filters with nominal cutoff frequencies selected to prevent aliasing. At a nominal cutoff frequency of 15 Hz, the calculated breakpoint frequencies were 18 and 19 Hz for the first and second poles respectively. A higher nominal cutoff frequency of 1800 Hz (1800 Hz at pole 1 and 1900 Hz at pole 2) was used on the handwheel angle channel.

4.4 Post Processing Filters

Most sensor data were filtered in post processing with 6-Hz 12-pole, 2-pass, phaseless digital Butterworth filters using Matlab software. Wheel lift height measurements were filtered with one-pass, digital running average filters set to 200 ms.

5.0 TEST MANEUVERS

Two maneuvers were used in Phase VIII: the Slowly Increasing Steer and the NHTSA Fishhook. This chapter describes each test maneuver, and describes how each was performed.

5.1 Slowly Increasing Steer

The Slowly Increasing Steer maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in SAE J266 [12]. Although Slowly Increasing Steer tests can be used to provide important handling information, NHTSA's Rollover Resistance tests only require the data output from the maneuver to define handwheel input magnitudes.

5.1.1 Determination of Maximum Steering Input Magnitude

In previous rollover research phases, Slowly Increasing Steer tests performed by NHTSA used handwheel angles that endeavored measure linear range and maximum quasi steady state lateral acceleration. While maximum lateral acceleration data is interesting, it is not required when determining a vehicles NCAP rollover resistance rating. For this reason, the authors decided to "abbreviate" the Slowly Increasing Steer maneuver so as to only steer the vehicle enough to assess its linear range lateral acceleration performance. Since vehicles have different lateral acceleration-to-steering gains, establishing a fixed handwheel angle was not deemed appropriate. For example, consider the data produced during tests performed with the 1992 Ford F150 and 1992 Honda Civic in Phase VI (see Figure 5.1). The handwheel angle of the F150 at approximately 0.41 g, a lateral acceleration considered to be near the upper bound of the linear range, was 75 degrees. This handwheel angle produced a lateral acceleration of 0.65 g during a similar test performed with the Civic, 59 percent greater than that of the F150.

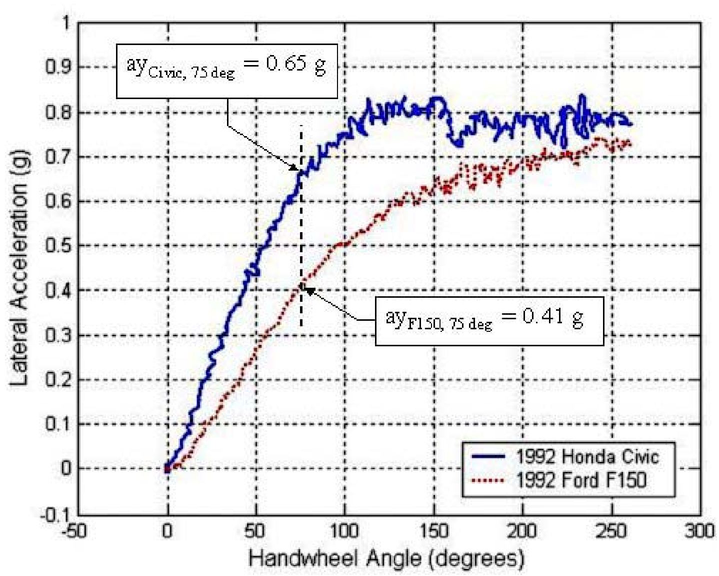


Figure 5.1. Comparison of handwheel angle versus lateral acceleration cross plots for a 1992 Honda Civic and a 1992 Ford F-150.

To determine the most appropriate Slowly Increasing Steer handwheel angle for a given vehicle, a preliminary left steer test was performed. The test speed during this test was held constant at 50 mph via throttle modulation, and the steering input ranged from 0 to 30 degrees, applied at 13.5 degrees per second. The magnitude of this input was selected because it was believed to be capable of producing a steady state lateral acceleration within the linear range for any light vehicle. Using the ratio of steady state handwheel position and lateral acceleration established by this test, the steering input of the Slowly Increasing Steer maneuver was derived using the below equation:

Equation 5.1

$$\frac{30\ degrees}{a_{y,30\ degrees}} = \frac{\delta_{SIS}}{0.55g}$$

where,

$a_{y,30\ degrees}$ was the raw lateral acceleration produced with a constant handwheel angle of 30 degrees during a test performed at 50 mph

δ_{SIS} was the steering input that, if the relationship of handwheel angle and lateral acceleration was linear, would produce a lateral acceleration of 0.55 g during a test performed at 50 mph

Note that $a_{y,30\ degrees}$ is raw data, not corrected for the effects of roll, pitch, and yaw. Also, the authors acknowledge the relationship of handwheel angle and *corrected* lateral acceleration data is often not linear at 0.55 g. Furthermore, previously collected NHTSA data[7] indicate the magnitude of raw 0.55 g acceleration data is typically reduced by approximately 9.6 percent to 0.497 g, when corrected for roll, pitch, and yaw, just outside of the linear range for most vehicles, as shown in Figure 5.2. Removing the effect of accelerometer offset (error due to the accelerometer not being positioned at the vehicle's actual center of gravity) typically reduces the magnitude of these data by an additional 0.07 percent. The importance of Equation 5.1 is that it simply provided experimenters with a direct, in-the-field way of determining an appropriate steering input for which to proceed with further tests for a given vehicle.

[7] NHTSA's Phase VI rollover research data [2] was used for this comparison. The Phase VI test vehicle fleet consisted of nine sport utility vehicles, six pickups, five minivans, and six passenger cars.

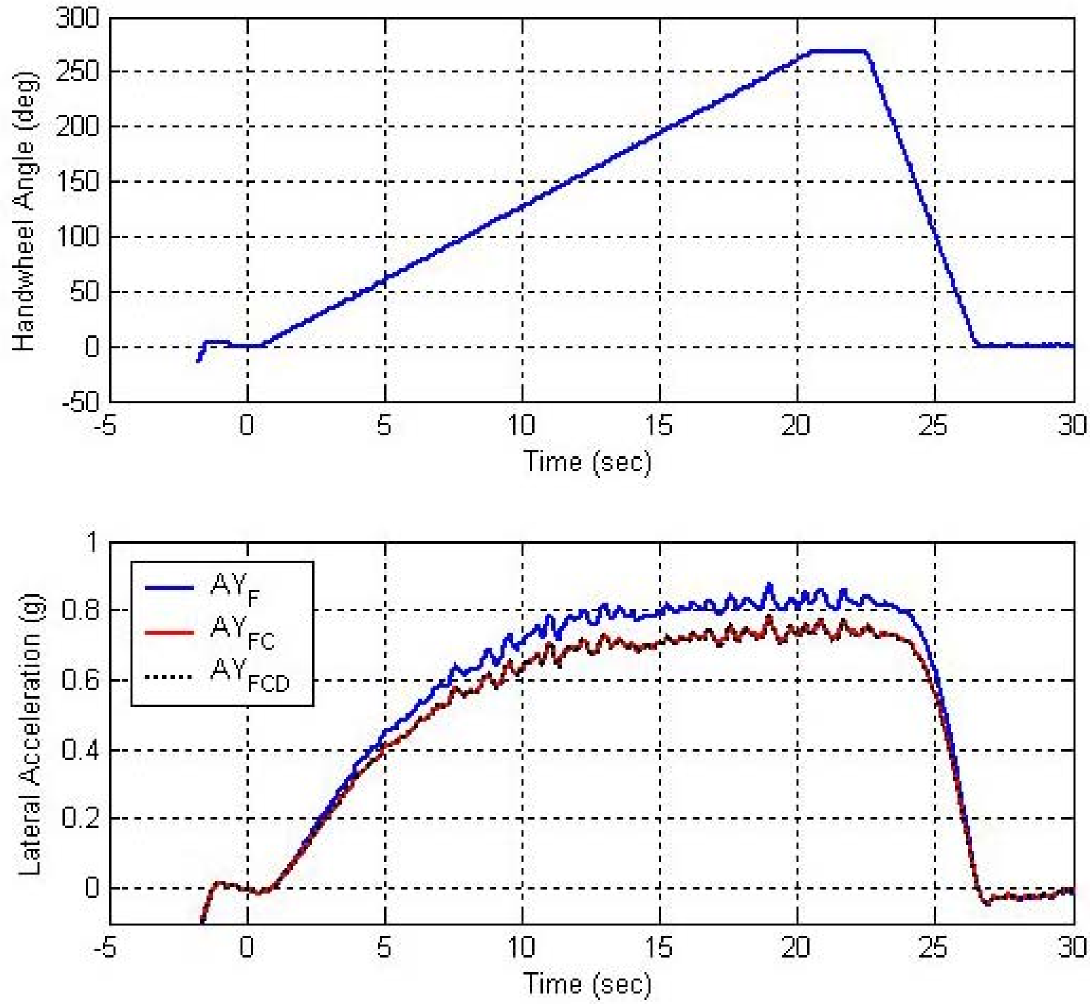


Figure 5.2. Comparison of filtered lateral acceleration data (AY_F) to that which has been a) filtered and corrected for roll angle effects (AY_{FC}), and b) filtered, corrected for roll angle effects, and corrected for accelerometer offset from the vehicle's C.G. (AY_{FCD}). Differences between AY_{FC} and AY_{FCD} are typically small, and are therefore difficult to see in the above figure.

5.1.2 Test Conduct and Output

Once the desired steering input was calculated, Slowly Increasing Steer tests were executed in a manner identical to that used in previous rollover research phases. To begin the maneuver, the vehicle was driven in a straight line at 50 mph. The driver was instructed to maintain as constant a test speed as possible before, during, and after the steering inputs using smooth throttle modulation. At time zero, handwheel position was linearly increased from zero to the handwheel position calculated with Equation 5.1 at a rate 13.5 degrees per second, as shown in Figure 5.3, and held constant for two seconds. The handwheel was then returned to zero as a convenience to the driver. The maneuver was performed to the left and to the right. Three repetitions of each test condition were performed.

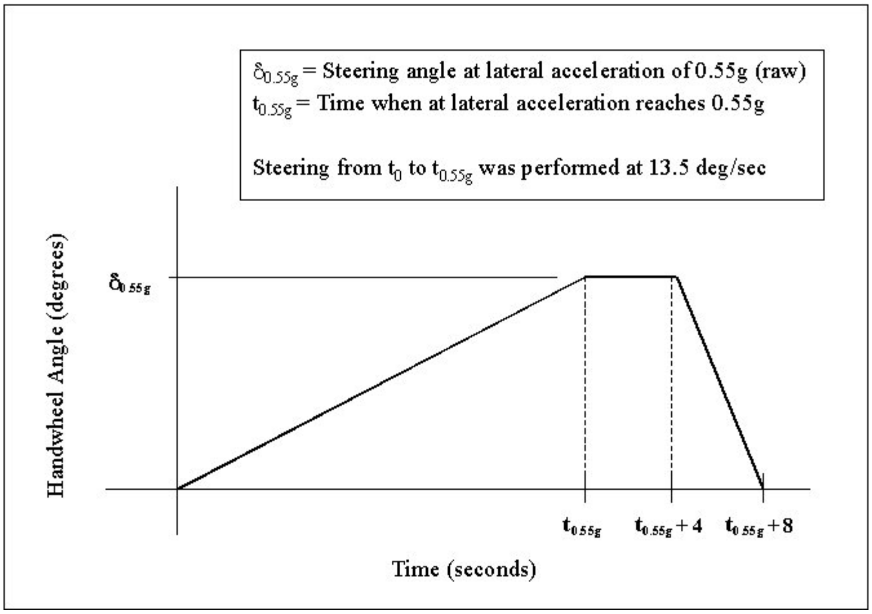


Figure 5.3. Slowly Increasing Steer maneuver description.

When lateral acceleration data collected during Slowly Increasing Steer tests was plotted with respect to time, a first order polynomial best-fit line was found to accurately describe the data from 0.1 to 0.375 g. NHTSA defines this as the linear range of the lateral acceleration response. Note that the upper bound of this range has been reduced from the 0.4 g used by NHTSA during previous rollover research phases. For some vehicles, the lateral acceleration response observed during Slowly Increasing Steer tests began to diverge (began to go non-linear) slightly before 0.4 g had been achieved. Reducing the upper bound to 0.375 has addressed this issue and has improved the fit of the regression line used to describe how well it describes the test data. Using the slope of the best-fit line, the average of handwheel positions at 0.3 g was calculated using data from each of the six Slowly Increasing Steer tests performed for each vehicle. This average handwheel position was used to calculate NHTSA Fishhook steering inputs, as described in the next sections of this report.

5.1.3 Facility Requirements and Tire Wear

Since NHTSA does not require measurement of maximum lateral acceleration when determining a vehicle's NCAP rollover resistance rating, performing Slowly Increasing Steer tests with handwheel inputs capable of producing lateral acceleration much beyond the linear range is unnecessary. This has some important practical implications. Obviously, the facility burden imposed by the abbreviated Slowly Increasing Steer is much less than that imposed by similar tests intended to also measure maximum lateral acceleration, as shown in Figures 5.4 and 5.5.

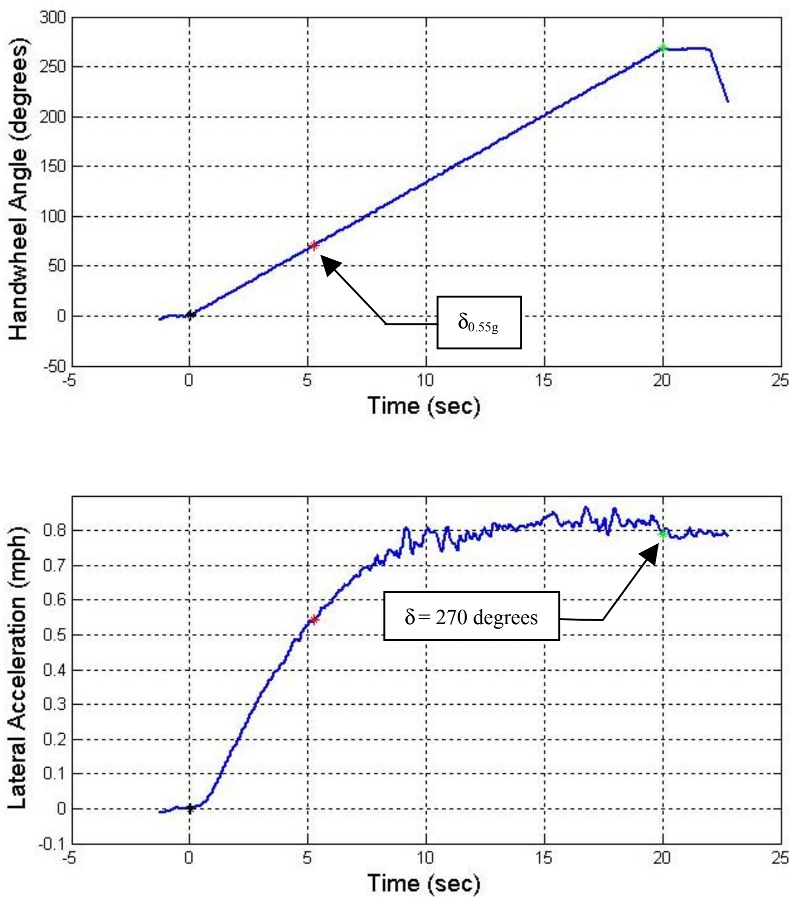


Figure 5.4. Handwheel angle and lateral acceleration observed during a Slowly Increasing Steer test performed with a 1994 Ford Taurus. Lateral acceleration data have been filtered, but not corrected for roll effects

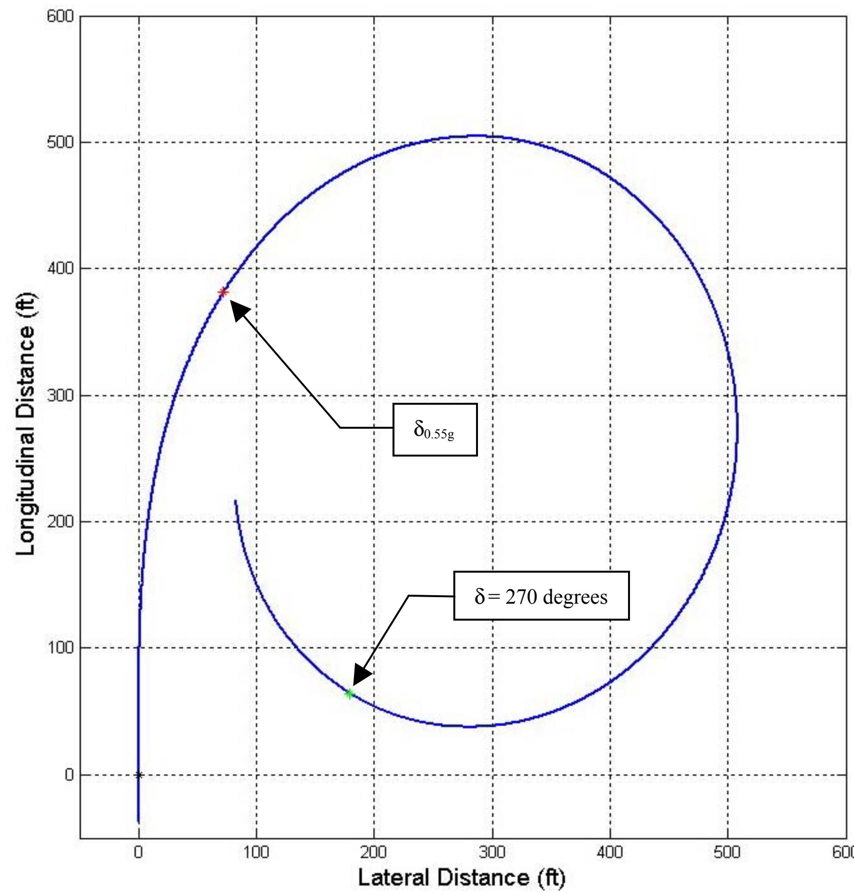


Figure 5.5. C.G. displacement observed during a Slowly Increasing Steer test performed with a 1994 Ford Taurus.

Another practical benefit of reducing the Slowly Increasing Steer input magnitude is a substantial reduction of tire wear. Due to the small slip generated during Slowly Increasing Steer tests performed in the linear range of lateral acceleration, and the small number of tests performed with each direction of steer, the tire wear produced during the abbreviated Slowly Increasing Steer test series is negligible. For this reason, the authors deemed the tire change between completion of the Slowly Increasing Steer test series and beginning of the Fishhook maneuver to no longer be required, and implemented the tire change procedure previously described in Section 3.3.4 for thirteen of the fourteen Phase VIII vehicles discussed in this report.

Use of this procedure lowered the per-vehicle costs associated with the tests described in this report by reducing the number of tire sets required and by eliminating the labor burden imposed by the related tire change, inner tube replacement, and wheel lift sensor calibration.

5.2 NHTSA Fishhook

The handwheel inputs defining the Fishhook maneuver approximate the steering a startled driver might use in an effort to regain lane position on a two-lane road after dropping two wheels off onto the shoulder. Of the nine Rollover Resistance maneuvers studied in the Agency's earlier Phase IV tests, only the Fishhook maneuver received "Excellent" ratings in each of the four maneuver evaluation factors (Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality). NHTSA considers the Fishhook to be the best overall maneuver for evaluating dynamic rollover propensity. Phase IV testing has demonstrated the handwheel input rates and magnitudes of the Fishhook are within the capabilities of an actual driver.

During Phases IV and V, Fishhook handwheel magnitudes were calculated by multiplying the handwheel angle producing an average of 0.3 g in the Slowly Increasing Steer maneuver by a scalar equal to 6.5. However, later tests performed during Phases VI and VII demonstrated that, for some vehicles, use of Fishhook steering inputs based on this scalar were so large they actually stifled the ability of the vehicle to produce two-wheel lift (the inputs overly saturating the tires, thereby degrading their lateral road holding capacity) [2]. In an attempt to improve maneuver severity, some tests performed in Phases VI and VII used reduced steering angles. Calculation of these smaller angles was accomplished by reducing the magnitude of the scalar used to determine Fishhook steering inputs from 6.5 to 5.5.

Since results from Phase VI and VII indicated use of reduced handwheel angles improved maneuver severity in certain cases (i.e., produced two-wheel lift with a vehicle that was unable to do so during tests performed with the larger scalar), all Phase VIII Fishhook tests were performed with procedures that included a provision that allowed the use of up to two scalars: 6.5 and 5.5.

As illustrated by the flowcharts contained in Appendix Figures A.1 through A.4, NHTSA's latest refinement of the Fishhook test procedure includes up to four components:

1. Default Procedure
2. Supplementary Procedure Part 1
3. Supplementary Procedure Part 2
4. Supplementary Procedure Part 3

For a given vehicle, the above components each differ in two ways: the steering angle utilized and the range entrance speeds the maneuvers are begun at. The following section explains each component.

5.2.1 Maneuver Overview

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, and when at the target speed, initiated the handwheel commands described in Figure 5.6 using a programmable steering machine. If a counterclockwise initial steer was input, the steering reversal following completion of the first handwheel ramp was to occur when the roll velocity of the vehicle was 1.5 degrees per second. If a clockwise initial steer was input, the steering reversal following completion of the first handwheel ramp occurred when the roll velocity of the vehicle was -1.5 degrees per second. The handwheel rates of the initial steer and countersteer were 720 degrees per second for all test vehicles. Following completion of the countersteer, handwheel position was maintained for three seconds. As a convenience to the test driver, the handwheel was then returned to zero.

Each Fishhook test series contained two sequences (with exceptions noted in the following sections): tests performed with left-right steering (first sequence), and tests performed with right-left steering (second sequence). The sequence of left-right tests always preceded those performed with right-left steering. In this study, right-left tests were not deemed necessary for some vehicles. This was because two-wheel lift occurred during left-right tests.

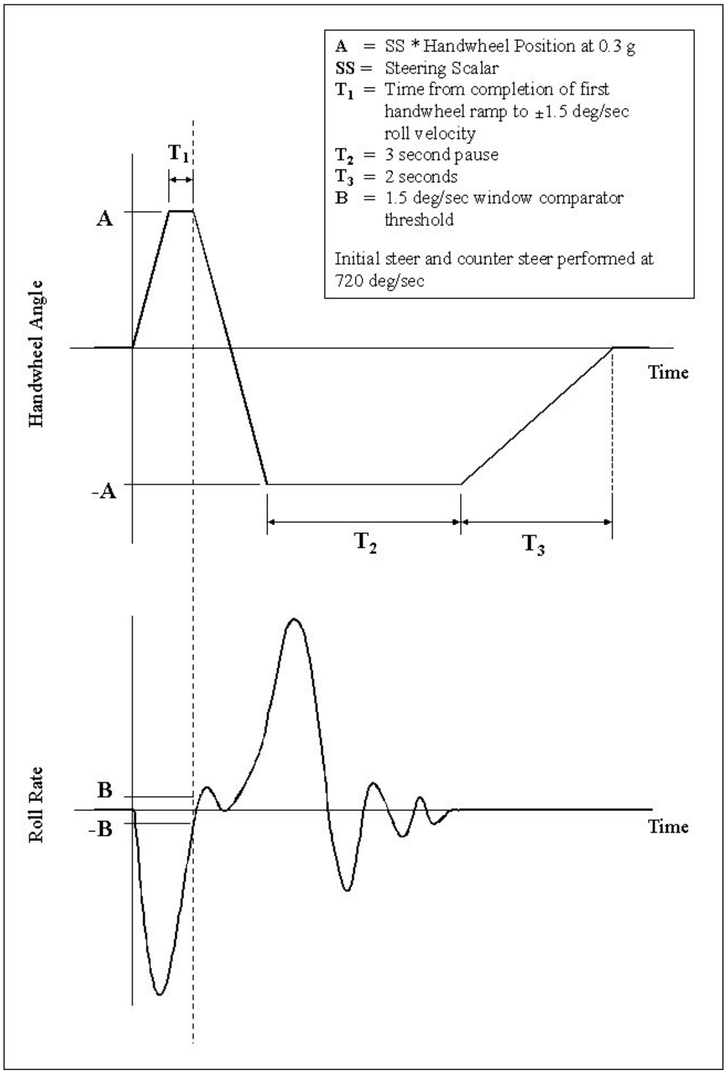


Figure 5.6. NHTSA Fishhook maneuver description.

5.2.2 Default Procedure

Fishhook handwheel angles were calculated with lateral acceleration and handwheel angle data (δ) collected during a series of six Slowly Increasing Steer tests (a total of three left-steer and three-right steer tests are performed). For each Slowly Increasing Steer test, a linear regression line was fitted to the lateral acceleration data from 0.1 to 0.375 g. Using the slopes of these regression lines, the handwheel angles at 0.3 g were determined for each individual test ($\delta_{0.3\text{ g}}$). The six handwheel angles are then averaged to produce an overall value ($\delta_{0.3\text{ g, overall}}$).

$$\delta_{0.3\text{ g, overall}} = (\left| \delta_{0.3\text{ g, left (1)}} \right| + \left| \delta_{0.3\text{ g, left (2)}} \right| + \left| \delta_{0.3\text{ g, left (3)}} \right| + \delta_{0.3\text{ g, right (1)}} + \delta_{0.3\text{ g, right (2)}} + \delta_{0.3\text{ g, right (3)}}) / 6$$

The Fishhook steering angles were calculated by multiplying $\delta_{0.3\text{ g. overall}}$ by a steering scalar (SS). The default steering scalar is 6.5.

$$\delta_{\text{Fishhook (Default)}} = 6.5 \times \delta_{0.3\text{ g, overall}}$$

As explained in Section 3.3.4, most [Default Procedure] Fishhook tests performed during Phase VIII began on the same tire set used for Slowly Increasing Steer tests performed with the same load configuration.

5.2.2.1 Maneuver Entrance Speed

For the sake of driver safety, and as a final step in the tire scrub-in procedure, each Default Procedure sequence began with a Maneuver Entrance Speed (MES) equal to 35 mph. The MES was measured at the initiation of the first steering ramp, and was increased until a termination condition was satisfied. The order of MES for a sequence was, in mph: 35, 40, 45, 47.5, 50. For each test run, the actual MES was required to be within 1 mph of the target MES.

Note: NHTSA's experience with the Fishhook maneuver indicates that an incremental increase in MES of 5 mph, up to 45 mph, minimizes tire wear without compromising test driver safety. However, when a MES greater than 45 mph is used, the severity of the responses produced with some vehicles can increase substantially from that observed at lesser entrance speeds. This is especially true if a vehicle has a propensity to oscillate in roll, and/or is able to produce two-wheel lift slightly less than NHTSA's threshold criterion of two inches. In some of these cases, the driver and/or experimenter may not be comfortable with a final 5 mph upwards increment in MES, and might, for the sake of driver safety, deviate from a test procedure that requires it. Generally speaking, such a deviation typically involves the experimenter's use of a more gradual 2.5 mph increase in MES.

To promote driver safety while also eliminating inconsistencies in the way NHTSA's Fishhook maneuvers were performed, the test procedure used in Phase VIII *required* a MES increment equal to 2.5 mph be used above 45 mph if a test performed at 45 mph did not produce two-wheel lift, regardless of the vehicle being evaluated. This will be a standard practice for all future Fishhook tests performed in support of the rollover NCAP.

5.2.2.2 Outrigger Contact

If either outrigger contacted the pavement without two-wheel lift during a Fishhook test run, the affected outrigger was raised 0.75 inches and the test was repeated at the same MES. If both safety outriggers contact the pavement without two-wheel lift, both outriggers were raised 0.75 inches and the test was repeated at the same MES.

5.2.2.3 Termination and Conclusion Conditions

A test <u>sequence</u> is terminated if an MES produced two-wheel lift and the MES is 45 mph or lower. If two-wheel lift is observed during a left-right sequence at 45 mph or lower, the [entire] <u>series</u> was terminated. If no two-wheel lift is observed during a left-right sequence, right-left tests were performed. If two-wheel lift was observed during a right-left sequence performed with a MES of 45 mph or lower, the test series was terminated.

If the MES capable of producing two-wheel lift during a left-right or right-left sequence was 47.5 mph or higher, a new set of tires was installed on the vehicle and the procedure described in Section 5.2.3.1 was implemented.

Although no instances of rim-to-pavement contact or tire debeading were observed during tests performed with the vehicles discussed in this study, it should be noted that had such events occurred, any remaining tests in the respective series would have been terminated.

A test series was deemed complete if both test sequences within a given series were performed at the maximum maneuver entrance speed without two-wheel lift, rim-to-pavement contact, tire debeading, or outrigger-to-pavement contact. If the Default Procedure was completed without encountering a termination condition, Supplemental Procedure Part 2, described in Section 5.2.3.2, was implemented.

The flowchart presented in Figure A.1 describes the sequence of events for the Default Test Series.

5.2.3 Supplemental Procedures

If the results of the Default Test Series required the implementation of the Supplemental Procedure Part 1, neither Supplemental Procedure Part 2 nor Part 3 was used.

Depending on the response of test vehicles to elements of the Fishhook protocol, Supplemental Procedure, Parts 1, 2, and 3 may have required a change in the steering scalar. The steering machine used by NHTSA had the capability for making such changes in vehicles during test sessions via selection of a pre-programmed steering schedule and the adjustment of overall steering angles.

5.2.3.1 Supplemental Procedure Part 1

(Verification of tip-ups seen during Default Procedure tests performed at 47.5 and/or 50 mph. Supplemental Procedure Part 1 used new tires.)

Note: Supplemental Procedure Part 1 was not used for any vehicle tested in the Multi-Passenger configuration (i.e., tests supporting the NCAP rating system) mentioned in this report, but it was used Toyota Tacoma 4x4 tests performed with the Nominal Load.

Following the tire scrub-in procedure outlined in Section 3.3.2, tests were performed with handwheel angles equal to $\delta_{\text{Fishhook (Default)}}$, as explained in Section 5.2.2. The steering combination (i.e., either left-right or right-left) that produced two-wheel lift in the Default Test Series was used. The first test was performed at a MES of 35 mph to remove any mold sheen remaining from the tire break-in procedure. The second test was performed at the MES at which two-wheel lift had been previously observed (i.e., with the previous tire set). If two-wheel lift was produced during the test performed with handwheel angles equal to $\delta_{\text{Fishhook (Default)}}$, the tip-up would be used in the determination of the vehicle's NCAP rollover resistance rating, and the test series would be deemed complete. Although the situation did not present itself during tests performed with the fourteen vehicles discussed in this report, if two-wheel lift was not produced and the MES was 47.5 mph, the MES would have been increased to 50 mph. If two-wheel lift was produced during the test performed with MES equal to 50 mph, the tip-up would have been used in the determination of the vehicle's NCAP rollover resistance rating, and the test series deemed complete.

If two-wheel lift was not produced at 50 mph with handwheel angles equal to $\delta_{\text{Fishhook (Default)}}$, tests would be performed with steering angles calculated by multiplying $\delta_{\text{0.3 g. overall}}$ by a steering scalar of 5.5.

$$\delta_{\text{Fishhook (Supplemental)}} = 5.5 \text{ x } \delta_{\text{0.3 g, overall}}$$

After the application of the reduced scalar, a test would be performed at the MES at which two-wheel lift had been observed in the Default Test Series using the same steering combination (i.e., either left-right or right-left). Although the situation did not present itself during tests performed with the fourteen vehicles discussed in this report, if two-wheel lift was produced during the test performed with handwheel angles equal to $\delta_{\text{Fishhook (Supplemental)}}$, the tip-up would have been used in the determination of the vehicle's NCAP rollover resistance rating, and the test series deemed complete. Also, if two-wheel lift was not produced and the MES was 47.5 mph, the MES would have been increased to 50 mph. If two-wheel lift was produced during the test performed with MES equal to 50 mph, the tip-up would have been used in the determination of the vehicle's NCAP rollover resistance rating, and the test series deemed complete. If two-wheel lift was not produced at 50 mph, the test series would have been deemed complete and the vehicle's rollover resistance would reflect a rating based on no two-wheel lift.

While no instances of rim-to-pavement contact or tire debeading were observed during tests performed with the vehicles discussed in this study, it should be noted that had such events occurred, any remaining Supplemental Procedure Part 1 tests would have been terminated. The flowchart presented in Figure A.2 describes the sequence of events for the Supplemental Procedure Part 1.

5.2.3.2 Supplemental Procedure Part 2

(Retest performed with a steering scalar of 5.5 if the Default Procedure did not produce two-wheel lift)

If two-wheel lift was not produced during tests performed with the Default Procedure, the steering scalar was reduced from 6.5 to 5.5. Using the same tires used for tests performed with the Default Test Series, tests were performed with steering angles calculated by multiplying $\delta_{\text{0.3 g. overall}}$ by a steering scalar of 5.5.

$$\delta_{\text{Fishhook (Supplemental)}} = 5.5 \text{ x } \delta_{\text{0.3 g, overall}}$$

For the sake of driver safety, the first test of the left-right sequence with the reduced steering scalar applied was performed at a MES of 45 mph. If this test did not produce two-wheel lift, the MES was increased to 47.5 mph. If the test with MES equal to 47.5 mph did not produce two-wheel lift, the MES was increased to 50 mph (the maximum MES used for Fishhook testing). If no two-wheel lift was observed during the left-right sequence, the right-left test sequence was initiated using the same process as the left-right sequence. Although the situation did not present itself during tests performed with the fourteen vehicles discussed in this report, if any test in the Supplemental Procedure Part 2 test series would have produced two-wheel lift, a new set of tires would be installed on the vehicle, and the procedure described Section 5.2.3.3 implemented.

While no instances of rim-to-pavement contact or tire debeading were observed during tests performed with the vehicles discussed in this study, it should be noted that had such events occurred, any remaining Supplemental Procedure Part 2 tests would have been terminated. The flowchart presented in Figure A.3 describes the sequence of events for the Supplemental Procedure Part 2.

5.2.3.3 Supplemental Procedure Part 3

(Verification of tip-ups seen during Supplemental Procedure Part 2 tests performed at 47.5 and/or 50 mph. Supplemental Procedure Part 3 used new tires.)

Note: Supplemental Procedure Part 3 was not used for any vehicle featured in this report. For this reason, the procedure is provided simply for the sake of completeness.

Had it been used, following the tire scrub-in procedure outlined in Section 4.6, two tests would have been performed with handwheel angles equal to $\delta_{\text{Fishhook (Supplemental)}}$. The steering combination that produced two-wheel lift during Supplemental Procedure Part 2 testing would have been used (i.e., either left-right or right-left). The first test would have been performed at a MES of 35 mph to remove any mold sheen remaining from the tire break-in procedure. The second test would have been performed at the MES that had produced two-wheel lift during Supplemental Procedure Part 2 testing (i.e., with the previous tire set). If two-wheel lift was produced during the test performed with handwheel angles equal to $\delta_{\text{Fishhook (Supplemental)}}$, the tip-up would be used in the determination of the vehicle's NCAP rollover resistance rating, and the test series deemed complete. If two-wheel lift was not produced and the MES was 45 mph, the MES would have been increased to 47.5 mph. If two-wheel lift was not produced and the MES was 47.5 mph, the MES would have been increased to 50 mph. If two-wheel lift was produced during any test performed during Supplemental Procedure Part 3, the tip-up would have been used in the determination of the vehicle's NCAP rollover resistance rating, and the test series deemed complete. If two-wheel lift was <u>not</u> produced during Supplemental Procedure Part 3, the test series would have been deemed complete and the vehicle's rollover resistance would reflect a rating based on no two-wheel lift.

If two-wheel lift was <u>not</u> produced during Supplemental Procedure Part 3, the test series was deemed complete and no tip-up was reported in the vehicle's NCAP Rollover Resistance Rating. Had rim-to-pavement contact or tire debeading been observed during any Supplemental Procedure Part 3 test, the test series would have been terminated. The flowchart presented in Figure A.4 describes the sequence of events for the Supplemental Procedure Part 3.

5.2.4 Summary of Phase VIII Fishhook Handwheel Angles

A summary of the Fishhook handwheel angles used in Phase VIII is presented in Table 5.1. Additionally, Table 5.1 presents the overall range of dwell times observed during tests performed with each vehicle and load configuration.

Table 5.1. Fishhook Handwheel Angles and Dwell Times.

Vehicle	Nominal Load				Multi-Passenger			
	$\delta_{ss} = 6.5$		$\delta_{ss} = 5.5$		$\delta_{ss} = 6.5$		$\delta_{ss} = 5.5$	
	Handwheel Angle (degrees)	Dwell Time Range (ms)	Handwheel Angle (degrees)	Dwell Time Range (ms)	Handwheel Angle (degrees)	Dwell Time Range (ms)	Handwheel Angle (degrees)	Dwell Time Range (ms)
2004 Volvo XC90	218	130 - 230	184	210 - 290	209	205 - 305	177	280 - 320
2004 Chevrolet Trailblazer 4x4	TNP				251	115 – 160	212	160 - 180
2004 Chevrolet Trailblazer 4x2	TNP				240	130 - 165	203	170 - 185
2003 Toyota 4Runner 4x4	246	115 - 165	208	165 - 185	253	130 - 175	214	185 - 200
2003 Toyota 4Runner 4x2	241	125 - 155	204	180 - 190	259	140 - 175	219	195 - 205
2003 Jeep Liberty 4x4	205	150 - 170	173	170 - 195	183	190 - 795	155	240 - 940
2003 Jeep Liberty 4x2	199	145 - 165	169	175 - 185	188	200 - 800	159	205 - 775
2003 Chevrolet Silverado 4x2	302	20 - 25	256	75 - 90	313	30 - 55	265	90 - 105
2003 Chevrolet Silverado 4x4	339	20 - 30	287	80 - 90	363	20 - 35	307	85 - 100
2003 Toyota Tacoma 4x4	331	25 - 55	TNP		374	30 - 60	TNP	
2003 Ford Explorer SportTrac 4x2	256	85 - 110	216	125 - 130	263	110 - 130	TNP	
2003 Ford Focus Wagon	204	135 - 705	173	165 - 175	210	165 - 185	178	205 - 580
2003 Toyota Echo[1]	TNP				217	170 - 265	184	250 - 595
2003 Subaru Outback	246	170 - 225	208	215 - 300	244	190 - 275	206	250 - 375

* Maximum roll angle was achieved before completion of the initial steering ramp.

Note: TNP = Test Not Performed. Vehicle did not require the use of steering calculated with $\delta_{ss} = 5.5$.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

6.0 STEERING MACHINE INPUT ASSESSMENT

In Phase VI, NHTSA evaluated its steering machines' ability to input the rates and angles commanded during J-Turn and Road Edge recovery maneuvers [2]. Although the steering machines were unable to generate the handwheel rates required by the J-Turn maneuver (1000 degrees/second) for some vehicles, those used for the Fishhook maneuver (720 degrees/second) were typically close to the target values. For example, the overall average handwheel rates of the steering reversals were within ± 10.0 percent of the commanded values.

To increase confidence that the NHTSA steering machines were operating correctly during Phase VIII, the methods used to assess the machine functionality in Phase VI were applied. Chapter 6 summarizes these results. Up to 16 Fishhook maneuvers were considered per vehicle. If two-wheel lift or tire debeading occurred, the number of test available for analysis was less. For the analyses discussed in this chapter, 202 tests were used to assess steering input performance. All Fishhook maneuvers were programmed with steering rates of 720 deg/sec.

6.1 Attaining Commanded Handwheel Angles

Tables 6.1 and 6.2 report the commanded handwheel angles, the actual testing ranges and the overall average handwheel angles on a per vehicle basis. Table 6.1 presents data collected during the Fishhook maneuvers performed with the commanded handwheel angles based on a steering scalar of 6.5, while Table 6.2 provides data from tests that used a steering scalar of 5.5.

When the tests based on a steering scalar of 6.5 were considered, the average initial steer inputs were within ± 3 degrees (± 1.4 percent) of their respective commanded values. The overall average reversals were within ± 5 degrees (± 1.9 percent) of the commanded targets. Three of the 14 vehicles used in this analysis, the 2003 Chevrolet Silverado 4x2, 2003 Chevrolet Silverado 4x4 and 2003 Toyota Tacoma 4x4, had dwell times shorter than 80 ms. For the reasons explained in [2], it was not possible to accurately determine the average initial steer magnitudes for these vehicles. The initial handwheel angles were verified graphically for these three vehicles, but since mean values could not be calculated, they are not reported in Table 6.1.

Looking to maneuvers performed with the 5.5 scalars, the average initial steer inputs were found to be within ± 3 degrees (± 1.6 percent) of their respective commanded values. The overall average reversals were within ± 3 degrees (± 1.0 percent) of the commanded angles. As indicated in Table 6.2, Fishhook tests based on a steering scalar of 5.5 were not performed with the Ford SportTrac or Tacoma 4x4. Since the Fishhook maneuvers using a steering scalar of 6.5 were always performed before those using a scalar of 5.5, and the tests based on scalar of 6.5 produced two-wheel lift, tests based on a steering scalar of 5.5 were not performed for these vehicles.

Table 6.1. Steering Inputs Used To Examine Fishhook Handwheel Angles (Steering Scalar = 6.5).

Vehicle	Initial Steer Magnitude (degrees)			Reversal Magnitude (degrees)		
	Commanded	Actual		Commanded	Actual	
		Range	Overall Average		Range	Overall Average
2004 Volvo XC90	209	207 - 212	209	209	204 - 215	209
2004 Chevrolet Trailblazer 4x4	251	247 - 249	248	251	248 - 249	249
2004 Chevrolet Trailblazer 4x2	240	236 - 237	237	240	237 - 239	238
2003 Toyota 4Runner 4x4	253	247 - 251	250	253	250 - 254	252
2003 Toyota 4Runner 4x2	259	256 - 258	257	259	257 - 259	258
2003 Jeep Liberty 4x4	183	181 - 183	181	183	181 - 184	182
2003 Jeep Liberty 4x2	188	173 - 187	185	188	186 - 190	188
2003 Chevrolet Silverado 4x2	313	N/A*	N/A*	313	309 - 316	313
2003 Chevrolet Silverado 4x4	363	N/A*	N/A*	363	362 - 364	363
2003 Toyota Tacoma 4x4	374	N/A*	N/A*	374	376	376
2003 Ford Explorer SportTrac 4x2	263	265 - 266	266	263	267 - 268	268
2003 Ford Focus Wagon	210	208 - 209	209	210	206 - 212	209
2003 Toyota Echo[1]	217	213 - 218	214	217	215 - 216	216
2003 Subaru Outback	244	243 - 246	244	244	244 - 246	245

*All handwheel dwell times observed during these test series were less than 80 ms. Therefore, it was impossible to distinguish the mechanical overshoot of the steering machine from its intended input.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

Table 6.2. Steering Inputs Used To Examine Fishhook Handwheel Angles (Steering Scalar = 5.5).

Vehicle	Initial Steer Magnitude (degrees)			Reversal Magnitude (degrees)		
	Commanded	Actual		Commanded	Actual	
		Range	Overall Average		Range	Overall Average
2004 Volvo XC90	177	171 - 178	175	177	174 - 184	178
2004 Chevrolet Trailblazer 4x4	212	209 - 210	209	212	210 - 211	210
2004 Chevrolet Trailblazer 4x2	203	200 - 201	201	203	201 - 202	201
2003 Toyota 4Runner 4x4	214	210 - 214	211	214	211 - 214	212
2003 Toyota 4Runner 4x2	219	216 - 218	217	219	218 - 219	218
2003 Jeep Liberty 4x4	155	152 - 154	153	155	153 - 155	155
2003 Jeep Liberty 4x2	159	155 - 158	157	159	158 - 161	159
2003 Chevrolet Silverado 4x2	265	263 - 265	264	265	262 - 268	265
2003 Chevrolet Silverado 4x4	307	308 - 309	309	307	309 - 310	310
2003 Toyota Tacoma 4x4	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
2003 Ford Explorer SportTrac 4x2	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
2003 Ford Focus Wagon	178	176 - 177	177	178	174 - 181	177
2003 Toyota Echo[1]	184	180 - 181	181	184	182 - 183	183
2003 Subaru Outback	206	206 - 207	206	206	206 - 207	207

*Supplemental procedures were not performed due to two-wheel lift.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

6.2 Attaining Commanded Handwheel Rates

On a per-vehicle basis, Tables 6.3 and 6.4 report the commanded handwheel rate, the actual testing ranges, the overall average handwheel rates, and range of regression coefficients of the best-fit lines used to determine the overall average handwheel rate. Table 6.3 provides data from tests performed with a steering scalar of 6.5, while Table 6.4 presents data from tests based on a steering scalar of 5.5. Regardless on the steering scalar magnitude, the overall average initial steer rates were within ± 20 deg/sec (± 2.8 percent) of the 720 deg/sec commanded value for each vehicle used in this study. The overall average rates of the steering reversals were within ± 14 deg/sec(± 2.2 percent) of the 720 deg/sec commanded value. Since the Ford SportTrac 4x2 and Toyota Tacoma 4x4 produced two-wheel lift during tests based on a steering scalar of 6.5, tests based on the 5.5 scalar were not performed, and are, therefore, not given in Table 6.4.

Table 6.3. Steering Inputs Used To Examine Fishhook Handwheel Rates (Steering Scalar = 6.5).

Vehicle	Initial Steer Magnitude				Reversal Magnitude			
	Commanded (deg/sec)	Actual			Commanded (deg/sec)	Actual		
		Range (deg/sec)	Overall Average (deg/sec)	R^2 Range		Range (deg/sec)	Overall Average (deg/sec)	R^2 Range
2004 Volvo XC90	720	697 - 738	721	0.9247 - 0.9950	720	710 - 721	717	0.9878 - 0.9990
2004 Chevrolet Trailblazer 4x4	720	714 - 719	716	0.9996 - 0.9999	720	710 - 713	712	0.9999 - 1.000
2004 Chevrolet Trailblazer 4x2	720	714 - 723	718	0.9991 - 0.9998	720	708 - 713	711	0.9999 - 1.0000
2003 Toyota 4Runner 4x4	720	707 - 726	721	0.9996 - 0.9998	720	701 - 709	704	0.9989 - 0.9998
2003 Toyota 4Runner 4x2	720	709 - 728	721	0.9983 - 0.9996	720	687 - 719	707	0.9979 - 0.9997
2003 Jeep Liberty 4x4	720	707 - 735	730	0.9838 - 0.9985	720	712 - 723	716	0.9966 - 0.9996
2003 Jeep Liberty 4x2	720	707 - 735	724	0.9779 - 0.9928	720	709 - 719	715	0.9969 - 0.9977
2003 Chevrolet Silverado 4x2	720	717 - 726	722	0.9989 - 0.9998	720	716 - 721	718	0.9998 - 0.9999
2003 Chevrolet Silverado 4x4	720	721 - 726	723	0.9993 - 0.9998	720	720 - 724	721	0.9998 - 1.0000
2003 Toyota Tacoma 4x4	720	727 - 732	730	0.9990 - 0.9992	720	722 - 723	722	0.9998
2003 Ford Explorer SportTrac 4x2	720	739 - 740	740	0.9996 - 0.9997	720	723 - 727	725	0.9997 - 0.9999
2003 Ford Focus Wagon	720	709 - 736	720	0.9973 - 0.9998	720	711 - 722	717	0.9995 - 0.9998
2003 Toyota Echo[1]	720	719 - 733	724	0.9964 - 0.9993	720	708 - 716	712	0.9995 - 0.9999
2003 Subaru Outback	720	719 - 739	732	0.9963 - 0.9986	720	721 - 726	724	0.9994 - 0.9996

*Maximum roll angle was achieved before completion of the initial steering input.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

Table 6.4. Steering Inputs Used To Examine Fishhook Handwheel Rates (Steering Scalar = 5.5).

Vehicle	Initial Steer Magnitude				Reversal Magnitude			
	Commanded (deg/sec)	Actual			Commanded (deg/sec)	Actual		
		Range (deg/sec)	Overall Average (deg/sec)	R^2 Range		Range (deg/sec)	Overall Average (deg/sec)	R^2 Range
2004 Volvo XC90	720	682 - 735	704	0.9274 - 0.9756	720	707 - 735	721	0.9870 - 0.9926
2004 Chevrolet Trailblazer 4x4	720	719 - 728	724	0.9992 - 0.9997	720	709 - 716	711	0.9999 - 1.0000
2004 Chevrolet Trailblazer 4x2	720	721 - 726	723	0.9991 - 0.9998	720	708 - 713	711	0.9999 - 1.0000
2003 Toyota 4Runner 4x4	720	727 - 734	730	0.9991 - 0.9996	720	705 - 712	709	0.9995 - 0.9997
2003 Toyota 4Runner 4x2	720	709 - 726	718	0.9973 - 0.9992	720	710 - 720	716	0.9995 - 0.9997
2003 Jeep Liberty 4x4	720	728 - 737	732	0.9971 - 0.9993	720	711 - 720	715	0.9992 - 0.9996
2003 Jeep Liberty 4x2	720	713 - 743	728	0.9739 - 0.9931	720	711 - 722	717	0.9944 - 0.9973
2003 Chevrolet Silverado 4x2	720	718 - 730	726	0.9991 - 0.9996	720	716 - 722	719	0.9998 - 0.9999
2003 Chevrolet Silverado 4x4	720	728 - 733	731	0.9991 - 0.9998	720	725 - 726	726	0.9999
2003 Toyota Tacoma 4x4	720	N/A*	N/A*	N/A*	720	N/A*	N/A*	N/A*
2003 Ford Explorer SportTrac 4x2	720	N/A*	N/A*	N/A*	720	N/A*	N/A*	N/A*
2003 Ford Focus Wagon	720	718 - 745	730	0.9979 - 0.9996	720	715 - 729	721	0.9994 - 0.9998
2003 Toyota Echo[1]	720	717 - 742	728	0.9968 - 0.9991	720	710 - 718	714	0.9993 - 0.9999
2003 Subaru Outback	720	716 - 751	736	0.9950 - 0.9974	720	723 - 728	726	0.9992 - 0.9994

*Supplemental procedures were not required due to two-wheel lift.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

7.0 ROLLOVER RESISTANCE MANEUVER TEST RESULTS

This chapter presents a summary of the two-wheel lifts, instances of rim-to-pavement contact, and tire debeading observed during Phase VIII testing. Plots showing the specific responses of each vehicle to the Fishhook maneuver are in the Appendix. Figures A.5 through A.56 show plots of various data channels for either: a) left-right and right-left tests performed with the Default Procedure at a MES of approximately 50 mph, or b) the tests that produced two-wheel lift. For each maneuver presented, two series of plots are provided. The first series contains vehicle speed, handwheel position, lateral acceleration, roll angle, and wheel lift information. The second series provide confirmation the steering machine was operating properly during the respective tests (i.e., whether the steering reversals were commanded within 10 ms of the roll rate signal entering the machine's window comparator).

7.1 Two-Wheel Lift

Two-wheel lift was defined as the occurrence of at least two inches of simultaneous lift of the inside wheels from the test surface. Two-wheel lift less than two inches was not considered. Furthermore, two-wheel lift great enough to require outriggers to suppress roll motion is reported simply as "two-wheel lift" as long as at least two inches of simultaneous two-wheel lift occurred before outrigger contact with the ground was made. Table 7.1 summarizes the maneuver entrance speeds required to produce two-wheel lift.

Of the fourteen vehicles discussed in this report, two produced two-wheel lift: the Ford Sport Trac 4x2 and the Toyota Tacoma 4x4. Two-wheel lift was observed during Fishhook tests performed with both load configurations for the Tacoma 4x4. Only tests performed with the Multi-Passenger load produced two-wheel lift with the Sport Trac 4x2.

A reduction of handwheel angle magnitude (i.e., changing δ_{ss} = 6.5 to δ_{ss} = 5.5) did not increase tip-up propensity. Every vehicle that produced two-wheel lift in Phase VIII did so when δ_{ss} = 6.5. No Fishhook tests based on δ_{ss} = 5.5 were performed for the vehicles that produced two-wheel lift when δ_{ss} = 6.5.

Repetition of tests that produced two-wheel lift with maneuver entrance speeds greater than or equal to 47.5 mph appears to be a good way of supporting previously collected data while simultaneously reducing the influence tire wear may have on tip-up propensity[8]. For example, in the case of the Tacoma 4x4, two-wheel lift was first observed during a left-right test performed at 48.3 mph in the Nominal Load configuration. Since the maneuver entrance speed was greater than or equal to 47.5 mph, a replacement tire set was installed and Supplemental Procedure Part #1 initiated. Following a low-speed test performed at 35.2 mph, use of a 48.2 mph maneuver entrance speed was able to produce two-wheel lift, confirming the previous test outcome was indeed valid. (**Note:** Since these tests did not use the Multi-Passenger load, the test outcome was not used for NCAP ratings).

[8]Recall that if two-wheel lift was observed during a test performed with a maneuver entrance speed ≥47.5 mph, a tire change is required before the test is repeated. This reduces the number of tests performed on a given tire set prior to the occurrence of two-wheel lift.

Although the Toyota Tacoma 4x4 and Ford Sport Trac 4x2 both produced two-wheel lift in the Multi-Passenger configuration, they did so when the maneuver entrance speed was less than 47.5 mph. For this reason, no repeated tests were performed (i.e., use of the Supplemental Procedures was not required).

7.2 Rim-to-Pavement Contact and Tire Debeading

No instances of pavement-to-rim contact or debeading of the tire from the rim were observed during Phase VIII tests performed with the fourteen vehicles mentioned in this study. As previously mentioned in Section 3.3.5, inner tubes were installed in all tires used during Phase VIII testing.

Table 7.1. Maneuver Entrance Speeds (in mph) For Which Two-Wheel Lift Was Produced (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Nominal Load				Multi-Passenger			
	$\delta_{ss} = 6.5$		$\delta_{ss} = 5.5$		$\delta_{ss} = 6.5$		$\delta_{ss} = 5.5$	
	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering	Left-Right Steering	Right-Left Steering
2004 Volvo XC90	--	--	--	--	--	--	--	--
2004 Chevrolet Trailblazer 4x4	TNP				--	--	--	--
2004 Chevrolet Trailblazer 4x2	TNP				--	--	--	--
2003 Toyota 4Runner 4x4	--	--	--	--	--	--	--	--
2003 Toyota 4Runner 4x2	--	--	--	--	--	--	--	--
2003 Jeep Liberty 4x4	--	--	--	--	--	--	--	--
2003 Jeep Liberty 4x2	--	--	--	--	--	--	--	--
2003 Chevrolet Silverado 4x2	--	--	--	--	--	--	--	--
2003 Chevrolet Silverado 4x4	--	--	--	--	--	--	--	--
2003 Toyota Tacoma 4x4	48.2	TNP			45.2	TNP		
2003 Ford Explorer SportTrac 4x2	--	--	--	--	45.1	TNP		
2003 Ford Focus Wagon	--	--	--	--	--	--	--	--
2003 Toyota Echo[1]	TNP				--	--	--	--
2003 Subaru Outback	--	--	--	--	--	--	--	--

Note: "TNP" = Test Not Performed; "**--**" = Two-wheel lift was not produced.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

8.0 CONCLUSIONS

The work presented in this report focused on testing the rollover resistance of 14 2003 or 2004 model year vehicles using the test maneuvers and procedures developed by NHTSA during previous phases of its Light Vehicle Rollover Research Program. Results from seven sport utility vehicles (SUVs), four pick-ups, and three passenger cars are presented. The vehicles were selected on the basis of their inclusion in the 2004 NCAP program. The 2003 vehicles were considered carry-over vehicles that were identical to 2004 vehicles in all respects that affect rollover resistance. Each vehicle was procured by NHTSA as new. Three vehicles were equipped with an electronic stability control system (ESC). If the vehicle was equipped with ESC, all tests were performed with the system enabled.

At the conclusion of Phase VI, NHTSA realized Fishhook maneuver severity could be better optimized if some minor adjustments to the test procedure were implemented. These adjustments, evaluated successfully in Phase VII, were incorporated into the test procedures used in Phase VIII.

This report presents results from tests performed in the Nominal and Multi-Passenger load configurations. However, it is important to recognize that unless a vehicle has the ability to seat only two passengers, all Fishhook tests performed in support of the NCAP rollover ratings will only use the Multi-Passenger load configuration. This configuration uses up to three 175 lb water dummies, and is intended to simulate a five-passenger load.

Of the 14 vehicles discussed in this report, two produced two-wheel lift: the Ford Sport Trac 4x2 and the Toyota Tacoma 4x4. Two-wheel lift was observed during Fishhook tests performed with both load configurations for the Tacoma 4x4. Only tests performed with the Multi-Passenger load produced two-wheel lift with the Sport Trac 4x2.

Use of the Fishhook's supplemental test procedures worked well for the vehicles discussed in this report. In the case of the Toyota Tacoma 4x4 in the Nominal Load configuration, Supplemental Procedure Part #1 tests performed with new tires were able to validate the two-wheel lift that occurred during a Default Procedure test series performed with Nominal Load.

A reduction of handwheel angle magnitude (i.e., changing δ_{ss} = 6.5 to δ_{ss} = 5.5) did not increase tip-up propensity. Of the Phase VIII vehicles discussed in this study, every vehicle that produced two-wheel lift did so when δ_{ss} = 6.5.

As a result of the tests performed in Phase VIII, the 2004 Ford Sport Trac 4x2 and the 2004 Toyota Tacoma 4x4 received NCAP rollover ratings based on a "tip-up" in the dynamic test component of NCAP's statistical model of rollover risk.

9.0 REFERENCES

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APPENDIX

Table A.1. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Baseline, Sorted By SSF In Descending Order, Per Vehicle Class).

Vehicle	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
2004 Volvo XC90	4803.5	51.13	26.55	-0.47	1.209	N/A	N/A	N/A
2004 Chevrolet Trailblazer 4x4	4702.4	52.36	26.28	-1.00	1.187	2799	598	2954
2004 Chevrolet Trailblazer 4x2	4516.2	53.53	26.77	-1.00	1.166	2741	602	2896
2003 Toyota 4Runner 4x4	4408.8	50.30	26.68	-1.79	1.165	2471	542	2651
2003 Toyota 4Runner 4x2	4162.1	52.72	27.05	-1.72	1.150	2417	553	2604
2003 Jeep Liberty 4x4	4113.0	48.10	26.10	-1.04	1.149	2079	539	2219
2003 Jeep Liberty 4x2	3942.2	49.73	26.74	-0.97	1.123	2036	536	2185
2003 Chevrolet Silverado 4x2	4761.4	60.04	26.19	-1.63	1.251	4039	693	4316
2003 Chevrolet Silverado 4x4	5091.1	57.47	27.40	-1.39	1.198	4272	699	4522
2003 Toyota Tacoma 4x4	3833.9	50.48	26.33	-1.31	1.123	2552	404	2695
2003 Ford Explorer SportTrac 4x2	4298.4	56.42	27.51	-1.14	1.067	2880	483	3058
2003 Ford Focus Wagon	2914.8	42.75	22.48	-0.80	1.295	1509	347	1648
2003 Toyota Echo[1]	2359.9	36.97	21.94	-1.14	1.282	984	262	1093
2003 Subaru Outback	3651.0	47.28	22.97	-0.93	1.264	1983	428	2155

[1]Logistic complications prevented certain baseline data from being collected. For this reason, measurements of a 2004 Volvo XC90 very similar to the vehicle actually used for the dynamic tests discussed in this study are presented in Table A.1.

[2]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

Table A.2. Overall Tire Summary (Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Size	Load Index / Speed Rating	Make	Model	DOT (First 7 Characters)	Inflation Pressure			
						Nominal Load		Multi-Passenger	
						Front	Rear	Front	Rear
2004 Volvo XC90	235/65R17	104H	Michelin	4x4 Synchrone	FKH2 F23	36	39	36	39
2004 Chevrolet Trailblazer 4x4	P245/70R16	106S	BF Goodrich	Open Trail T/A (TPC 1165)	AP9L 2E1	32	32	32	32
2004 Chevrolet Trailblazer 4x2	P245/70R16	106S	BF Goodrich	Open Trail T/A (TPC 1165)	AP9L 2E1	32	32	32	32
2003 Toyota 4Runner 4x4	P265/70R16	111S	Bridgestone	Dueler H/T 840	ELLJ DAK	32	32	32	32
2003 Toyota 4Runner 4x2	P265/70R16	111S	Bridgestone	Dueler H/T 840	ELLJ DAK	32	32	32	32
2003 Jeep Liberty 4x4	P215/75R16	101S	Goodyear	Wrangler ST	M6Y4 EYE	33	33	33	33
2003 Jeep Liberty 4x2	P215/75R16	101S	Goodyear	Wrangler ST	M6Y4 EYE	33	33	33	33
2003 Chevrolet Silverado 4x2	P235/75R16	106S	Goodyear	Wrangler ST (TPC 1152)	M63D DAW	35	35	35	35
2003 Chevrolet Silverado 4x4	P245/75R16	109S	Goodyear	Wrangler ST (TPC 1153)	4B70 DAD	35	35	35	35
2003 Toyota Tacoma 4x4	P265/70R16	111S	Bridgestone	Dueler H/T 689	7X72 PDD	26	26	26	26
2003 Ford Explorer SportTrac 4x2	P235/70R16	104S	Michelin	Cross Terrain Radial X	M37P H9A	30	35	30	35
2003 Ford Focus Wagon	P195/60R15	87T	Goodyear	Eagle RS-A	M6V9 LNE	32	32	32	32
2003 Toyota Echo	P185/60R15	84T	Bridgestone	Potenza RE92	ELCA DJB	32	32	32	32
2003 Subaru Outback	P225/60R16	97H	Bridgestone	Potenza RE92	OBXO C6A	30	29	30	29

Table A.3. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Nominal Load, Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
		Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
2004 Volvo XC90	5209.0	54.45	26.19	-0.40	1.225	3527	742	3831
2004 Chevrolet Trailblazer 4x4	4942.8	51.81	25.78	-0.70	1.210	3059	659	3262
2004 Chevrolet Trailblazer 4x2	4756.4	53.09	26.14	-0.60	1.194	3030	662	3219
2003 Toyota 4Runner 4x4	4668.0	51.05	26.10	-1.45	1.191	2797	614	3021
2003 Toyota 4Runner 4x2	4424.7	53.35	26.50	-1.48	1.174	2732	616	2956
2003 Jeep Liberty 4x4	4430.3	49.09	25.41	-0.81	1.180	2402	585	2593
2003 Jeep Liberty 4x2	4260.1	50.53	25.89	-0.58	1.160	2364	595	2560
2003 Chevrolet Silverado 4x2	5012.5	60.45	25.73	-1.37	1.274	4453	748	4767
2003 Chevrolet Silverado 4x4	5336.4	57.98	27.14	-1.11	1.209	4673	765	4673
2003 Toyota Tacoma 4x4	4092.6	50.88	25.73	-1.05	1.149	2882	469	3079
2003 Ford Explorer SportTrac 4x2	4525.7	56.17	27.02	-0.97	1.086	3175	537	3383
2003 Ford Focus Wagon	3206.5	42.72	21.69	-0.46	1.342	1807	397	1995
2003 Toyota Echo[1]	2609.8	38.01	21.04	-0.72	1.337	1180	317	1329
2003 Subaru Outback	3922.9	47.35	22.38	-0.62	1.297	2272	480	2489

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

Table A.4. Test Vehicle Weight, C.G. Location, and Mass Moments of Inertia (Multi-Passenger, Sorted By Baseline SSF In Descending Order, Per Vehicle Class).

Vehicle	Water Dummy Placement	Weight (lbs)	C.G.			SSF	Mass Moments of Inertia		
			Longitudinal (in)	Height (in)	Lateral Offset (in)		Pitch (ft-lb-sec^2)	Roll (ft-lb-sec^2)	Yaw (ft-lb-sec^2)
2004 Volvo XC90	2nd Row (3)	5711.3	57.36	26.87	-0.40	1.194	3659	788	3950
2004 Chevrolet Trailblazer 4x4	2nd Row (3)	5443.9	55.89	26.39	-0.60	1.182	3267	697	3458
2004 Chevrolet Trailblazer 4x2	2nd Row (3)	5254.3	57.20	26.77	-0.50	1.165	3212	695	3404
2003 Toyota 4Runner 4x4	2nd Row (3)	5172.5	55.04	26.96	-1.46	1.153	2991	652	3186
2003 Toyota 4Runner 4x2	2nd Row (3)	4929.8	57.29	27.28	-1.40	1.141	2893	645	3106
2003 Jeep Liberty 4x4	2nd Row (3)	4933.9	53.29	26.14	-0.68	1.147	2584	632	2764
2003 Jeep Liberty 4x2	2nd Row (3)	4763.1	54.74	26.62	-0.49	1.128	2527	627	2719
2003 Chevrolet Silverado 4x2	2nd Row (3)	5513.1	62.80	26.56	-1.21	1.234	4551	784	4842
2003 Chevrolet Silverado 4x4	2nd Row (3)	5842.1	60.43	27.90	-1.02	1.176	4771	800	5059
2003 Toyota Tacoma 4x4	2nd Row (2) 3rd Row (1)*	4618.4	54.84	26.80	-0.87	1.103	3044	511	3212
2003 Ford Explorer SportTrac 4x2	2nd Row (3)	5030.9	59.46	27.92	-1.01	1.051	3266	571	3495
2003 Ford Focus Wagon	2nd Row (3)	3623.5	47.29	21.88	-0.20	1.330	1939	420	2129
2003 Toyota Echo[1]	2nd Row (3)	2907.4	42.10	21.30	-0.59	1.321	1271	327	1426
2003 Subaru Outback	2nd Row (3)	4223.7	50.03	22.56	-0.59	1.287	2361	497	2581

*One water dummy was positioned in the center of a simulated 3rd seating row in the bed. The second seating row of the extended cab included only two designated seating positions.

[1]Vehicle was equipped with 2004 model year springs, struts, and shock absorbers.

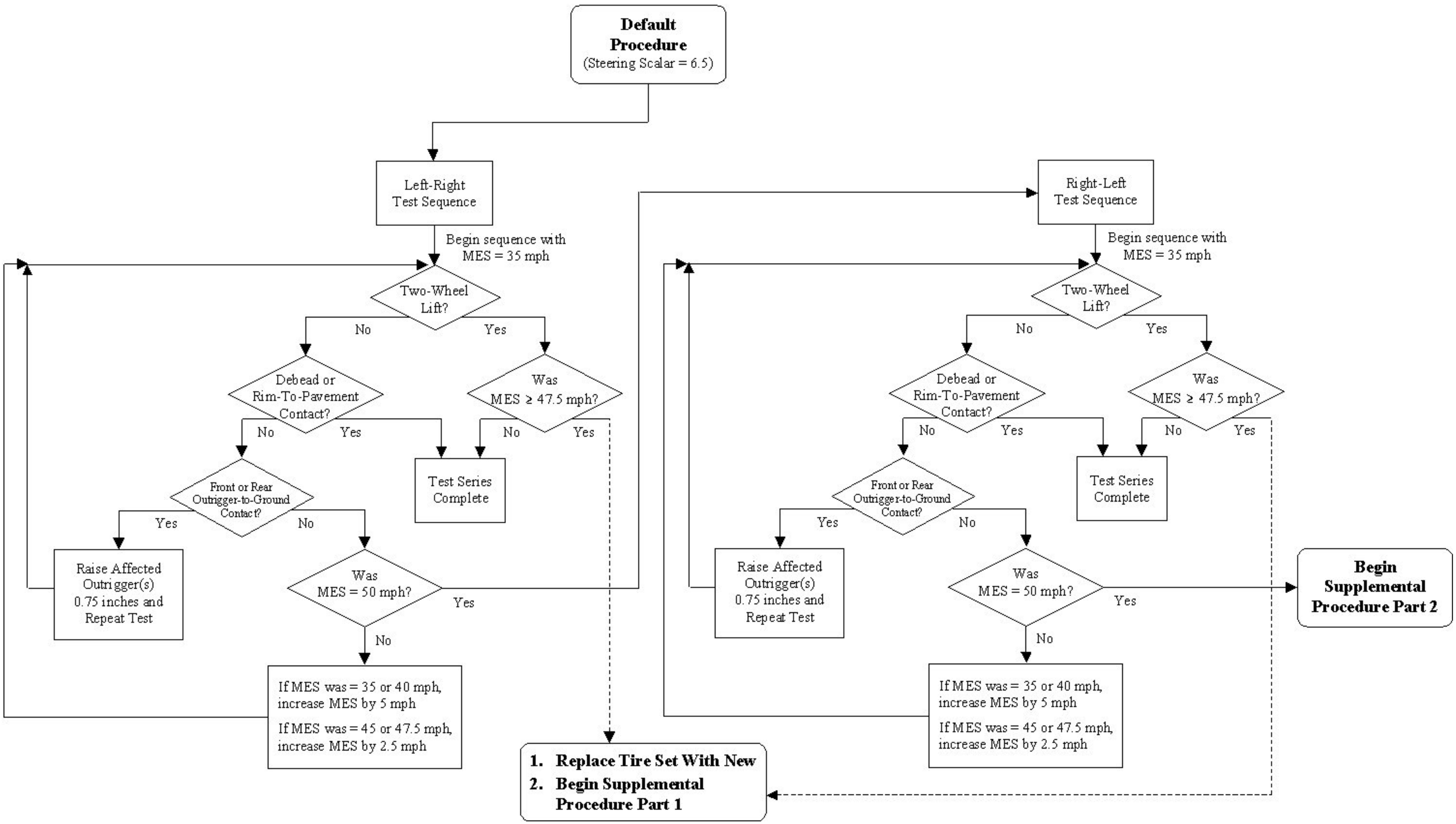

Figure A.1. Default Test Procedure.

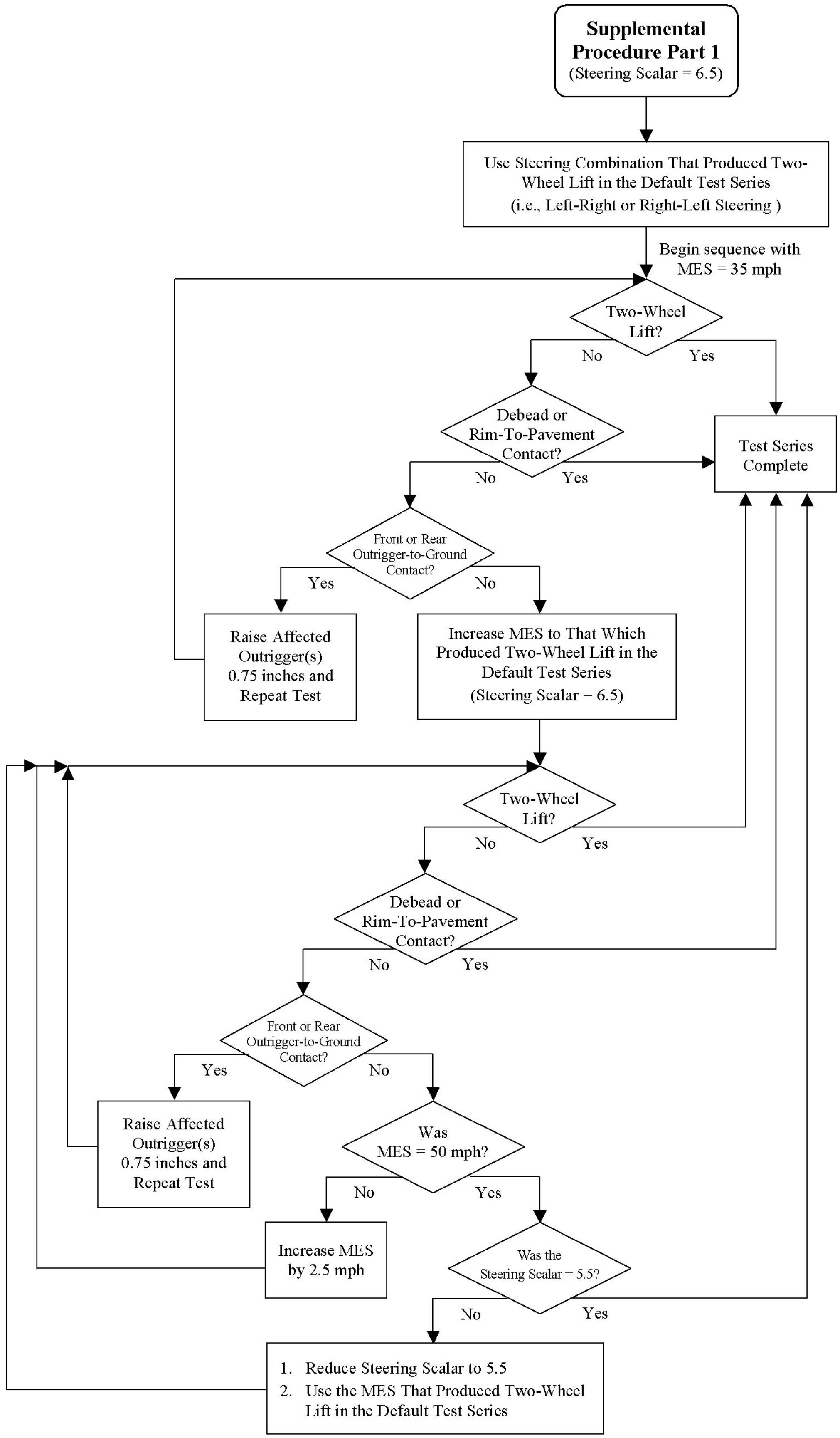

Figure A.2. Supplemental Procedure Part 1.

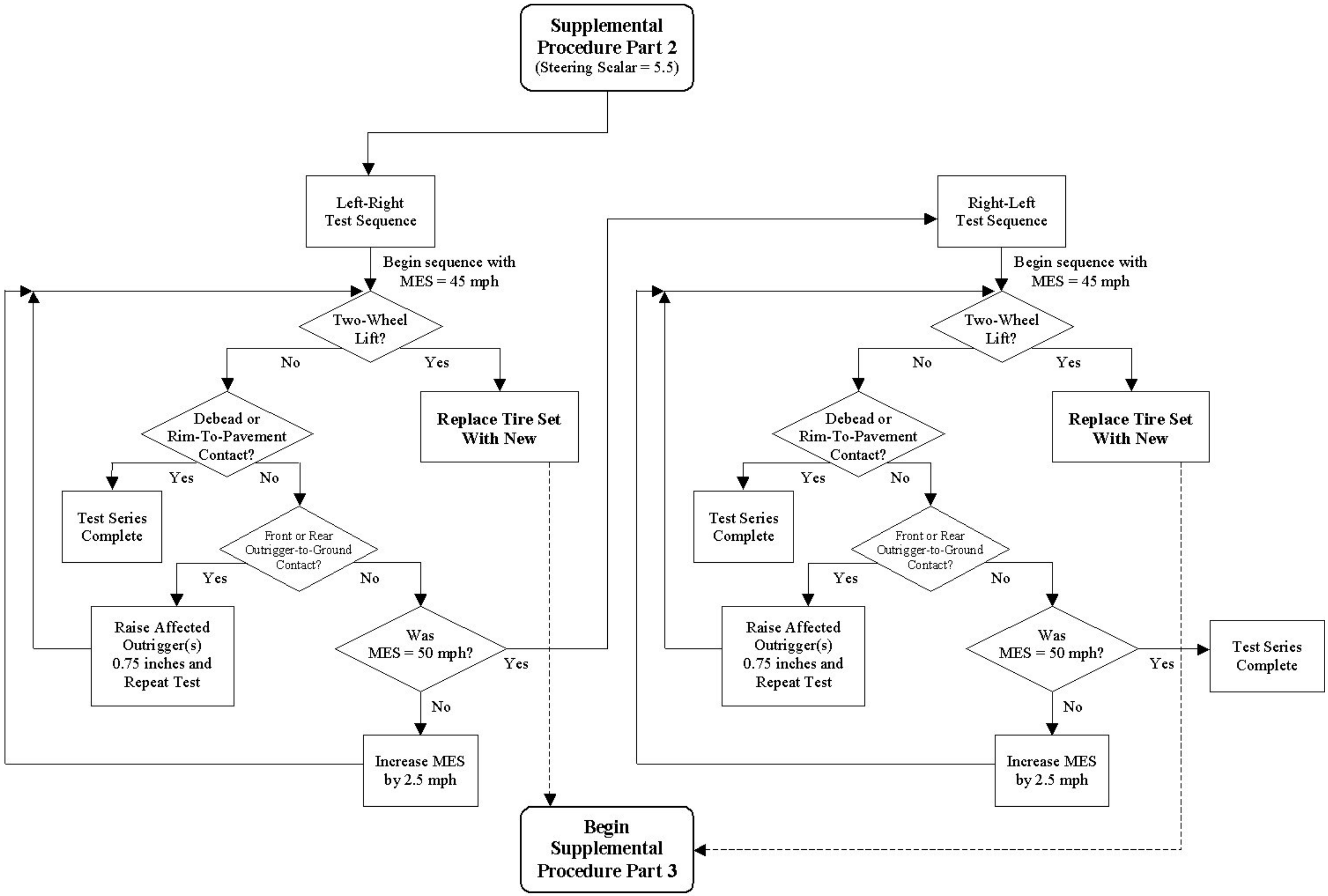

Figure A.3. Supplemental Procedure Part 2.

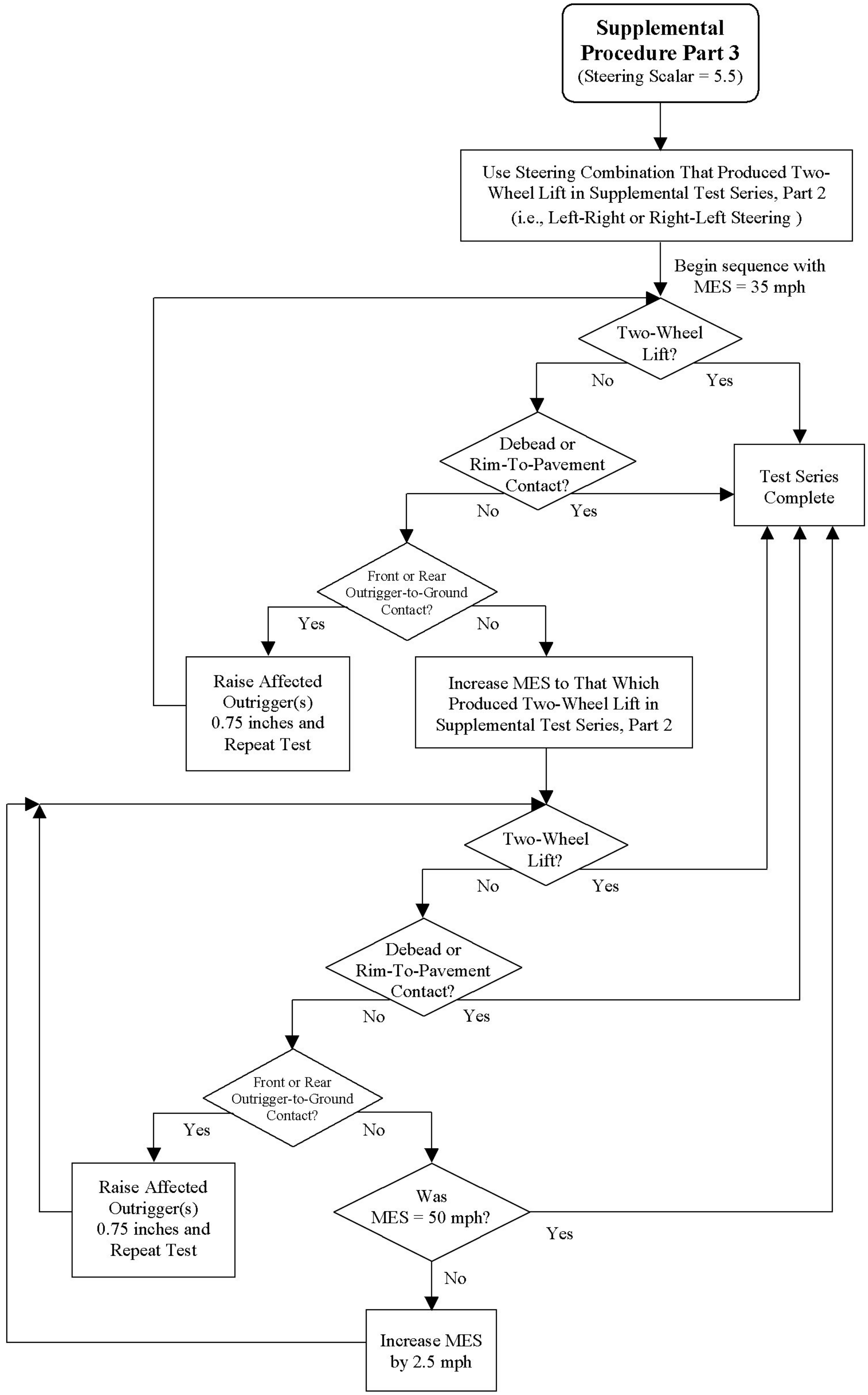

Figure A.4. Supplemental Procedure Part 3.

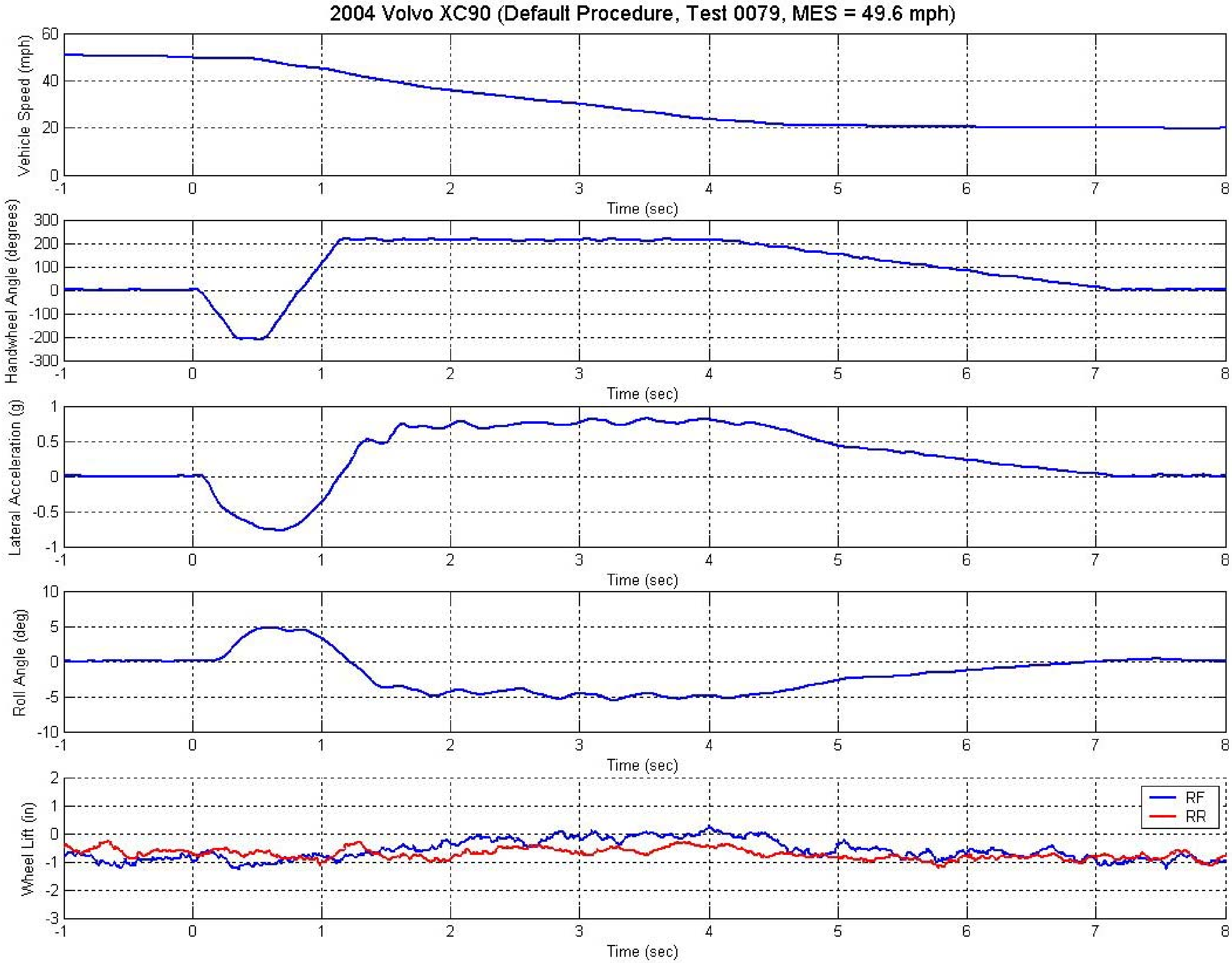

Figure A.5. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2004 Volvo XC90.

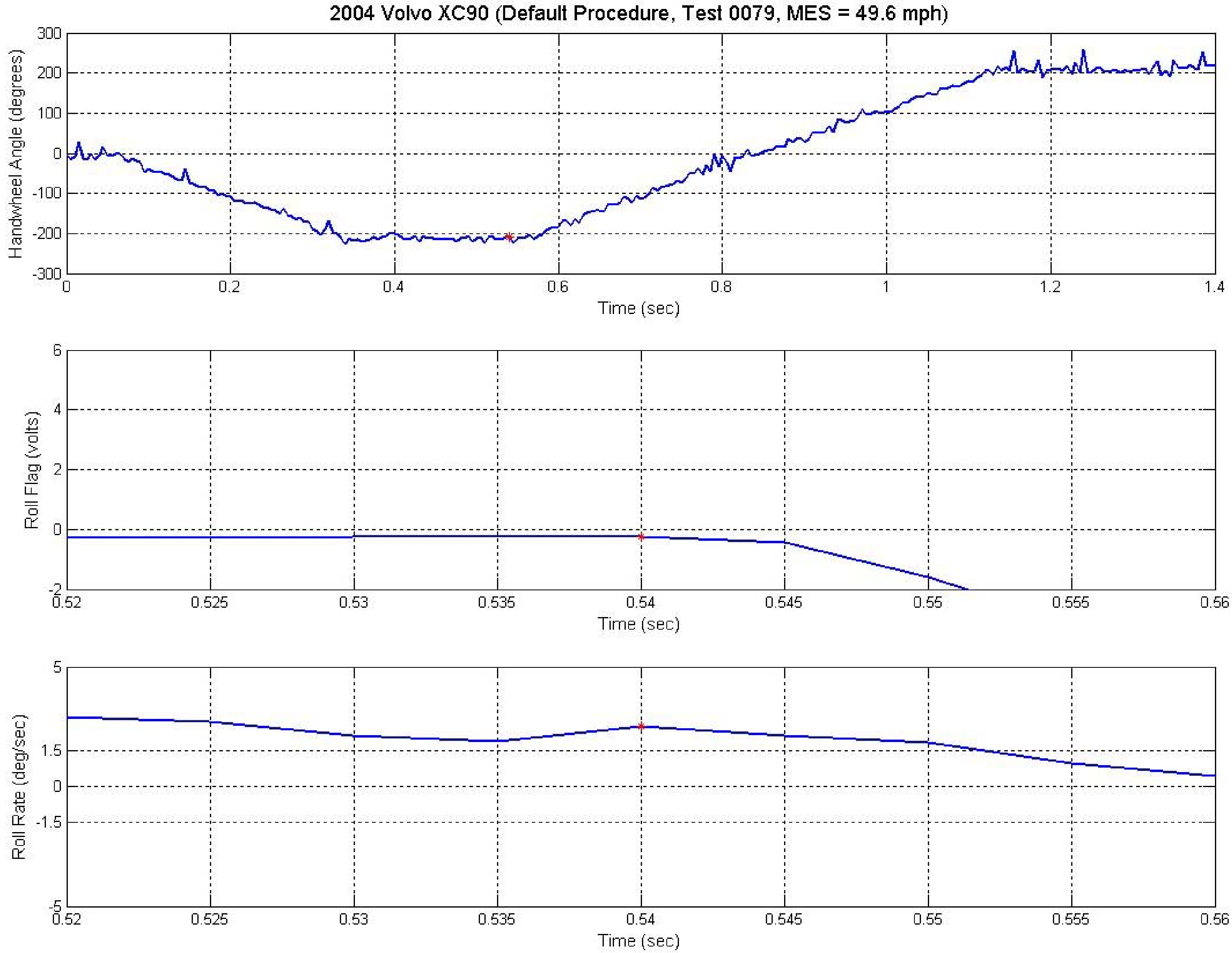

Figure A.6. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2004 Volvo XC90.

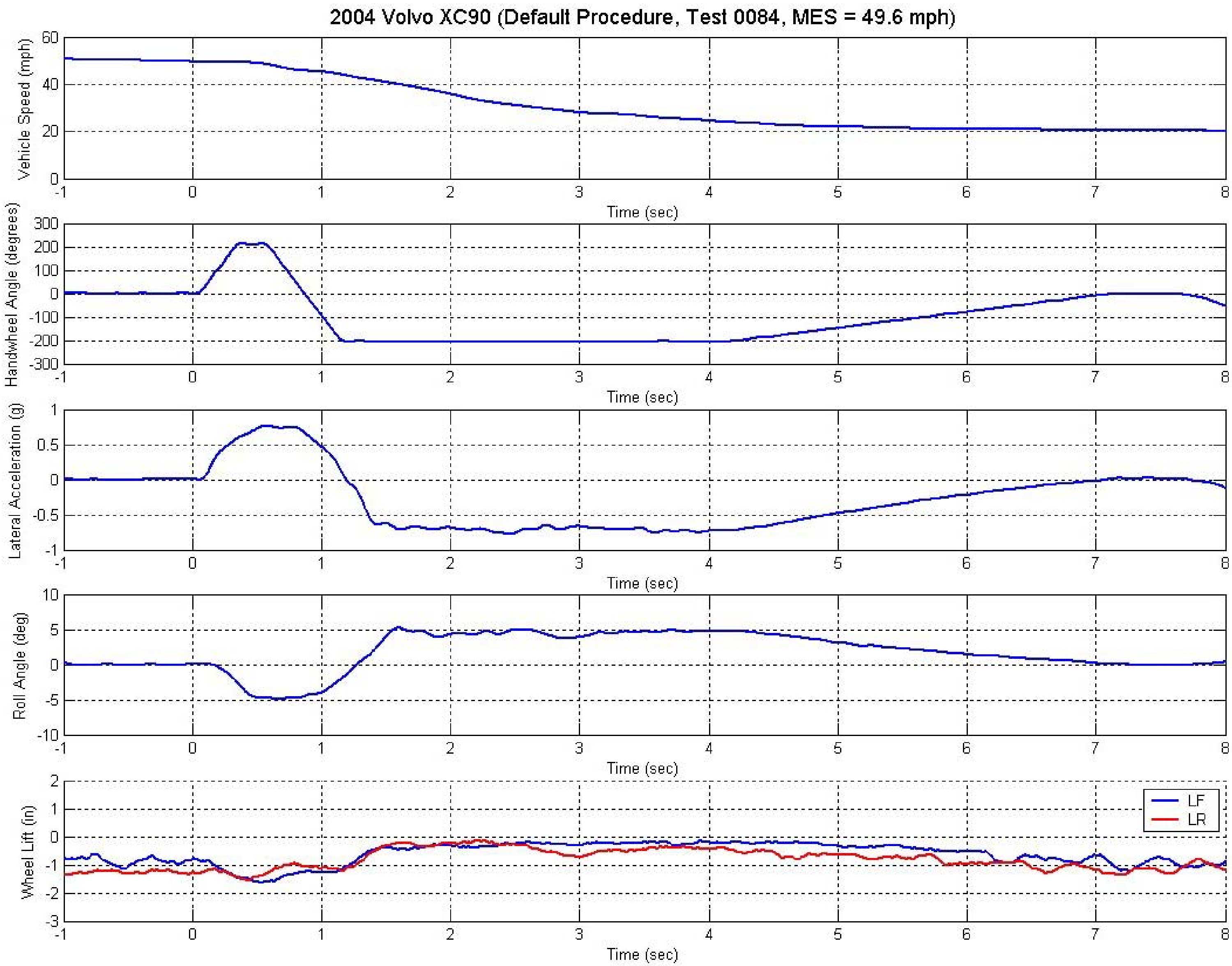

Figure A.7. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2004 Volvo XC90.

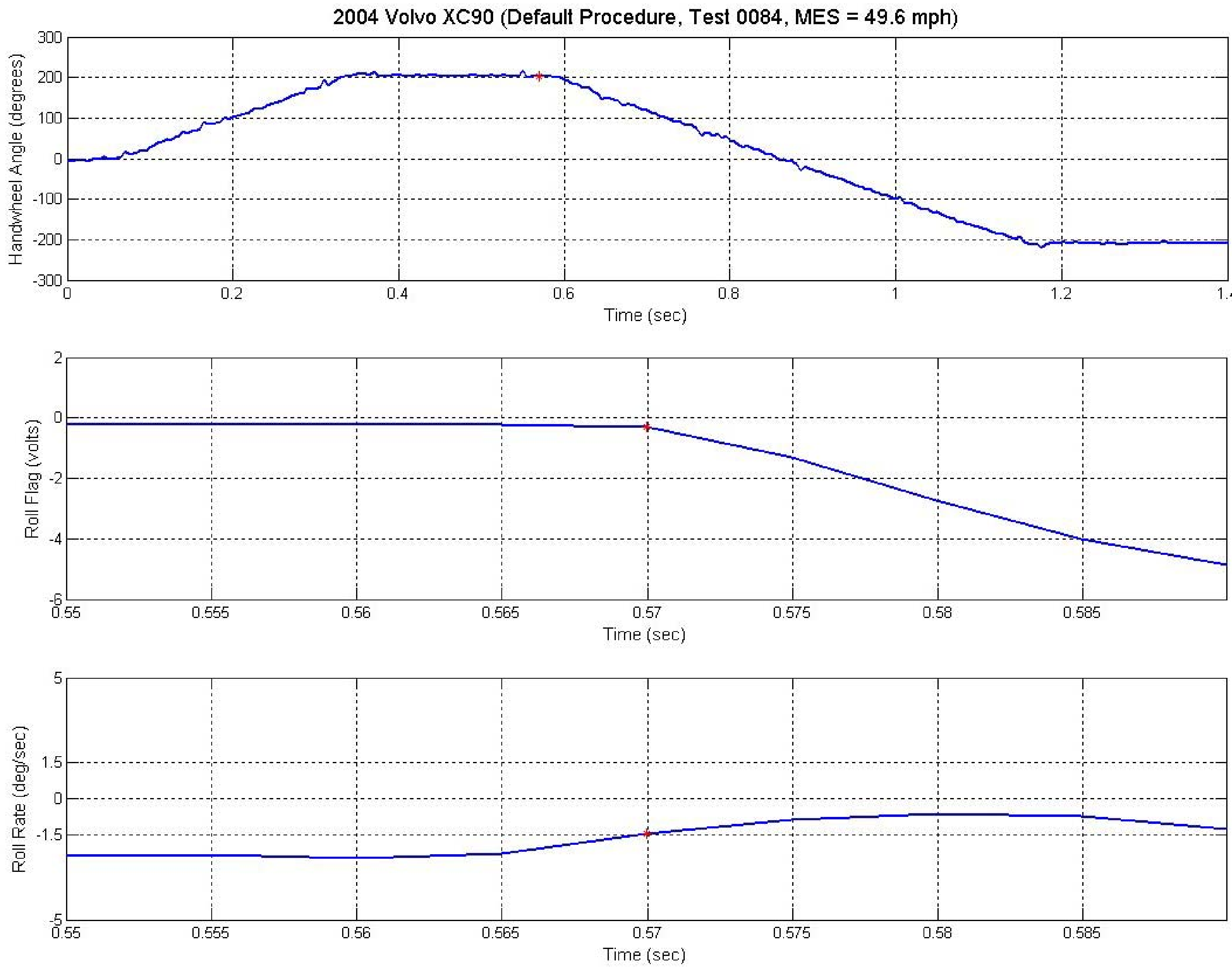

Figure A.8. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2004 Volvo XC90.

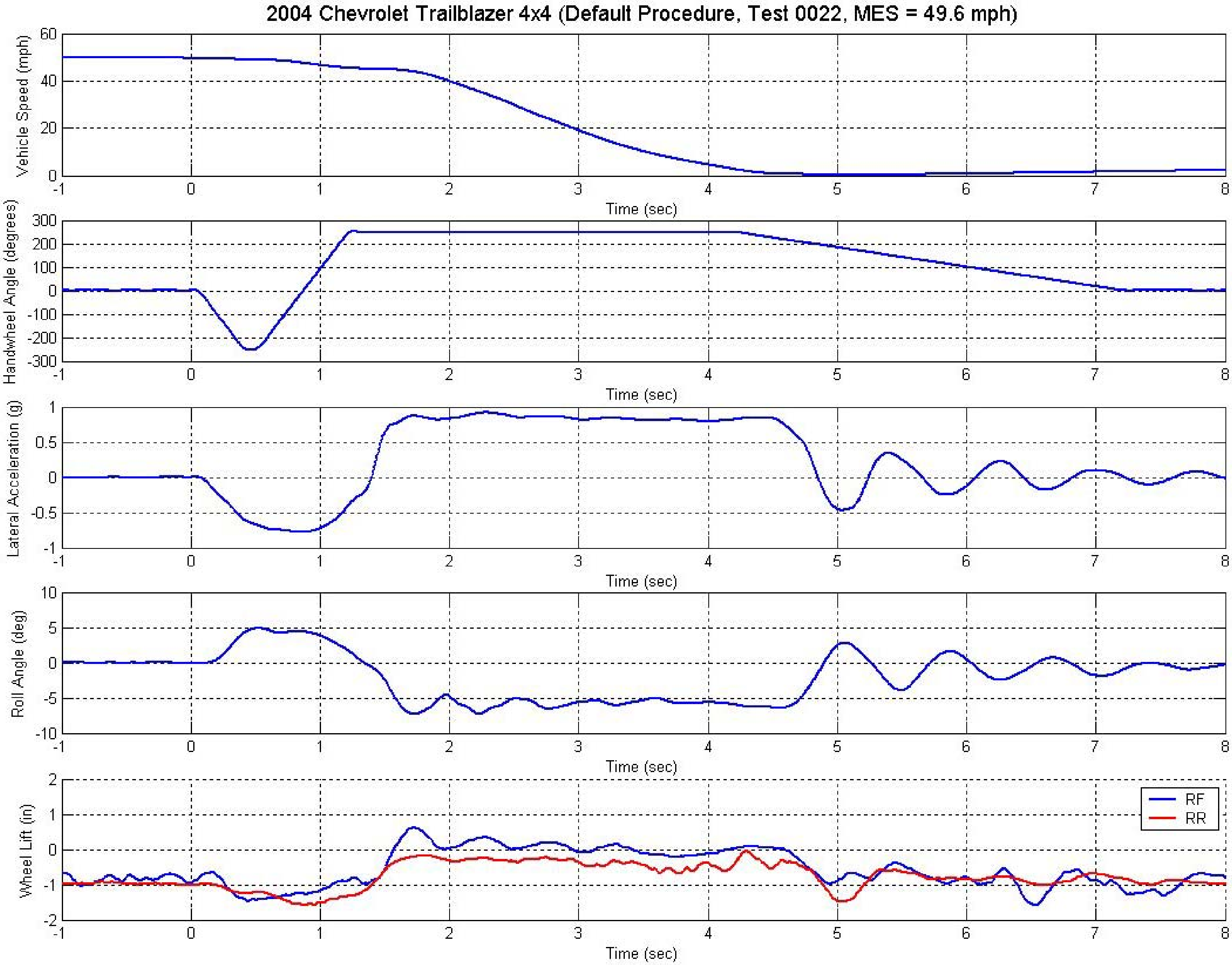

Figure A.9. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2004 Chevrolet Trailblazer 4x4.

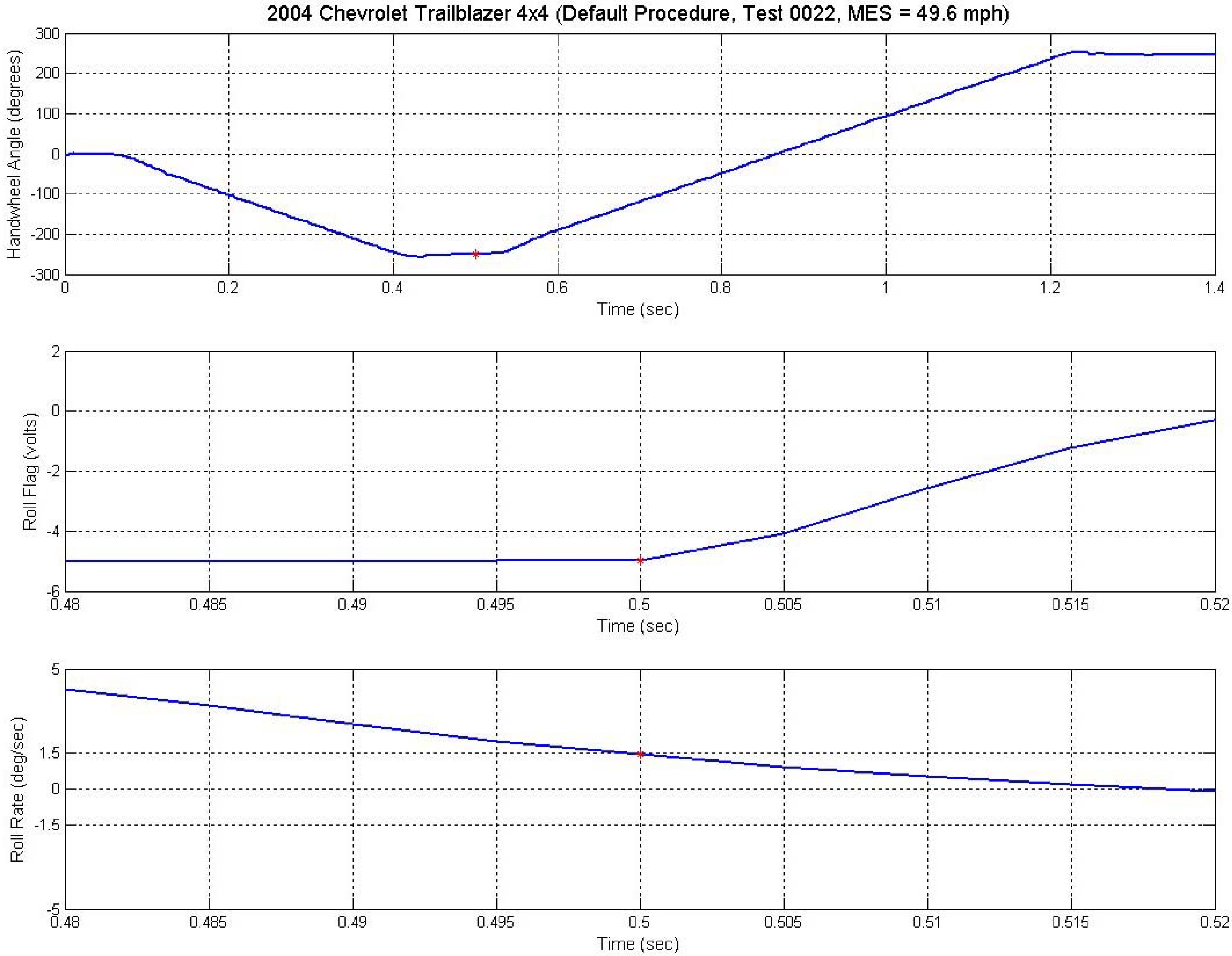

Figure A.10. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2004 Chevrolet Trailblazer 4x4.

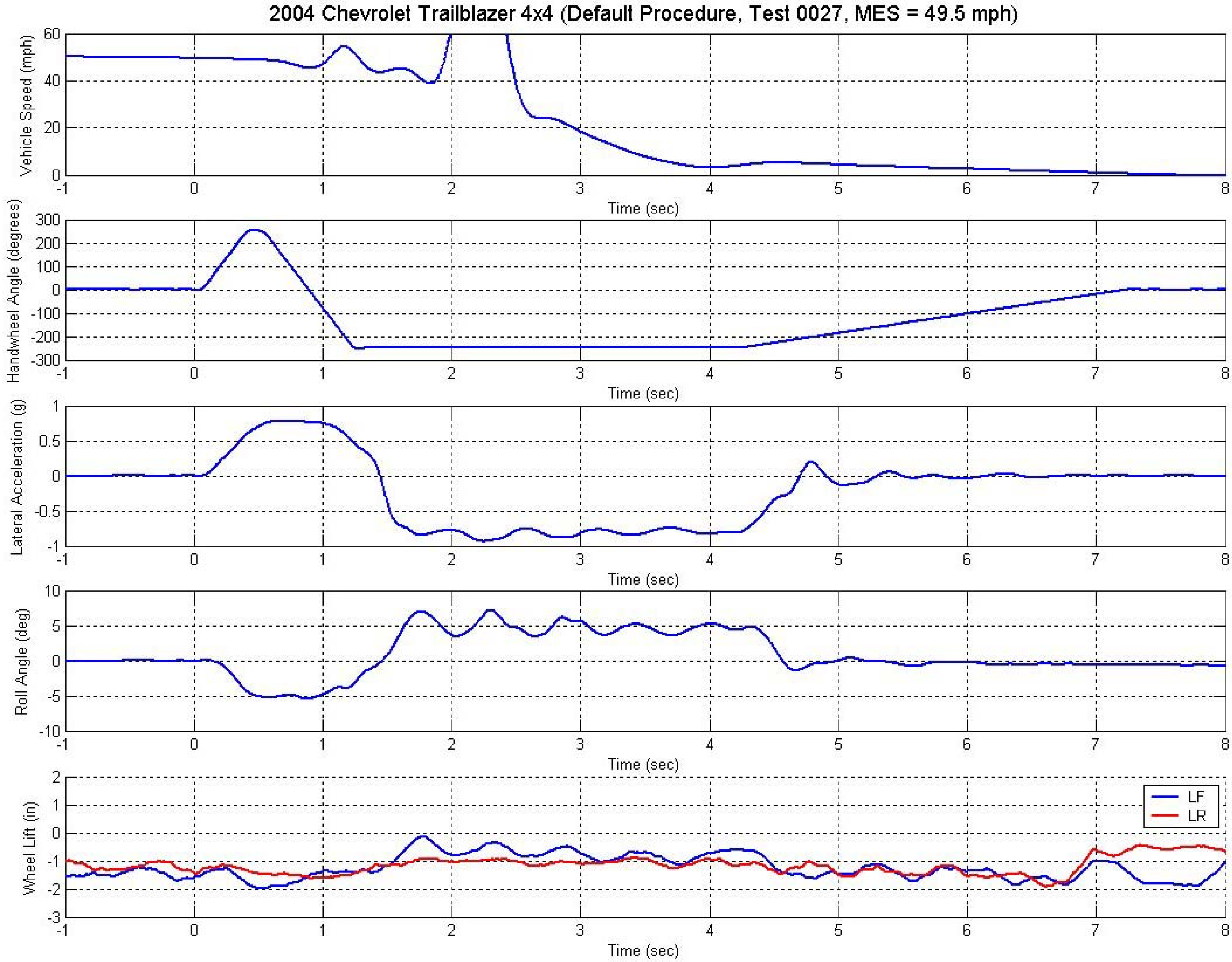

Figure A.11. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2004 Chevrolet Trailblazer 4x4.

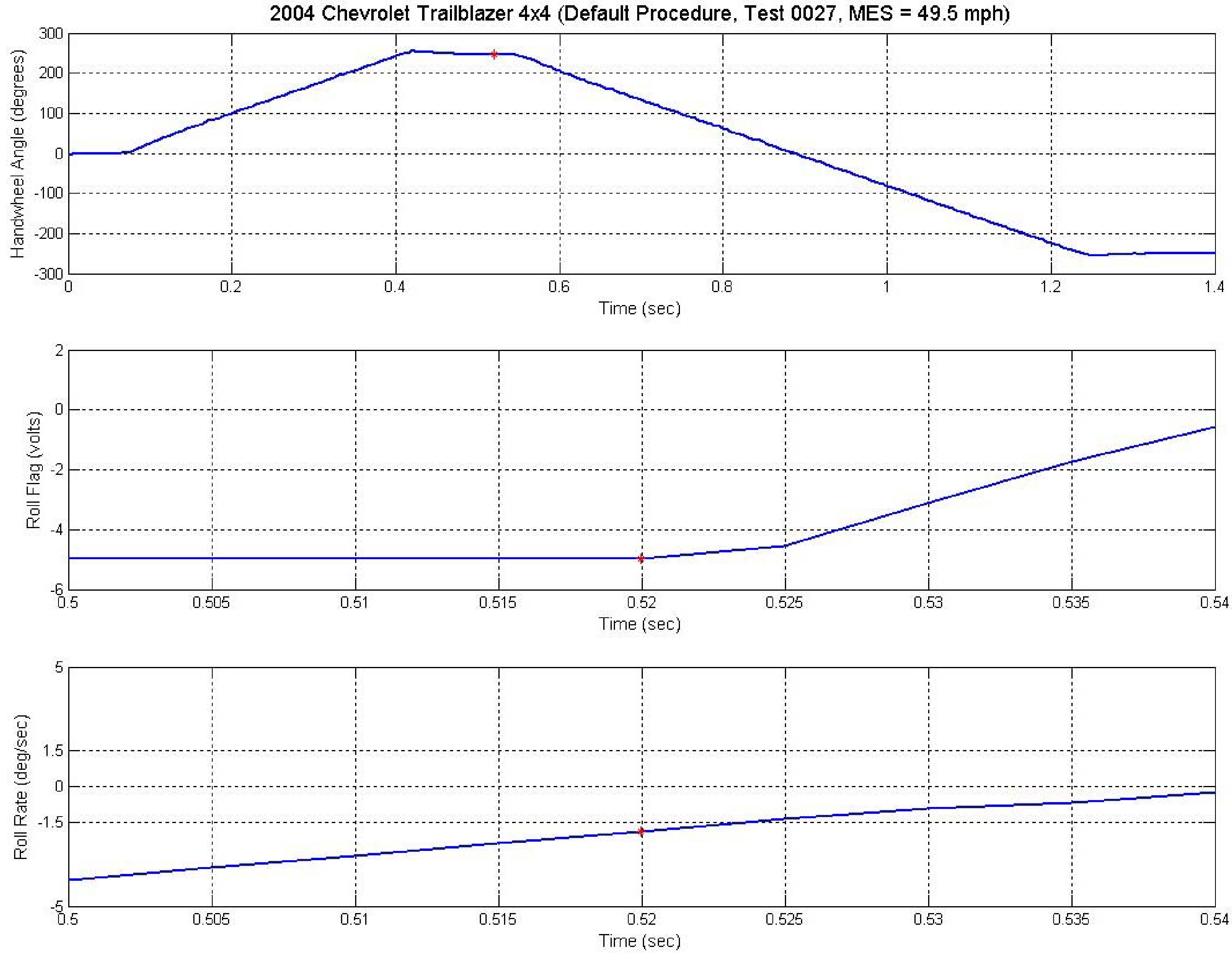

Figure A.12. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2004 Chevrolet Trailblazer 4x4.

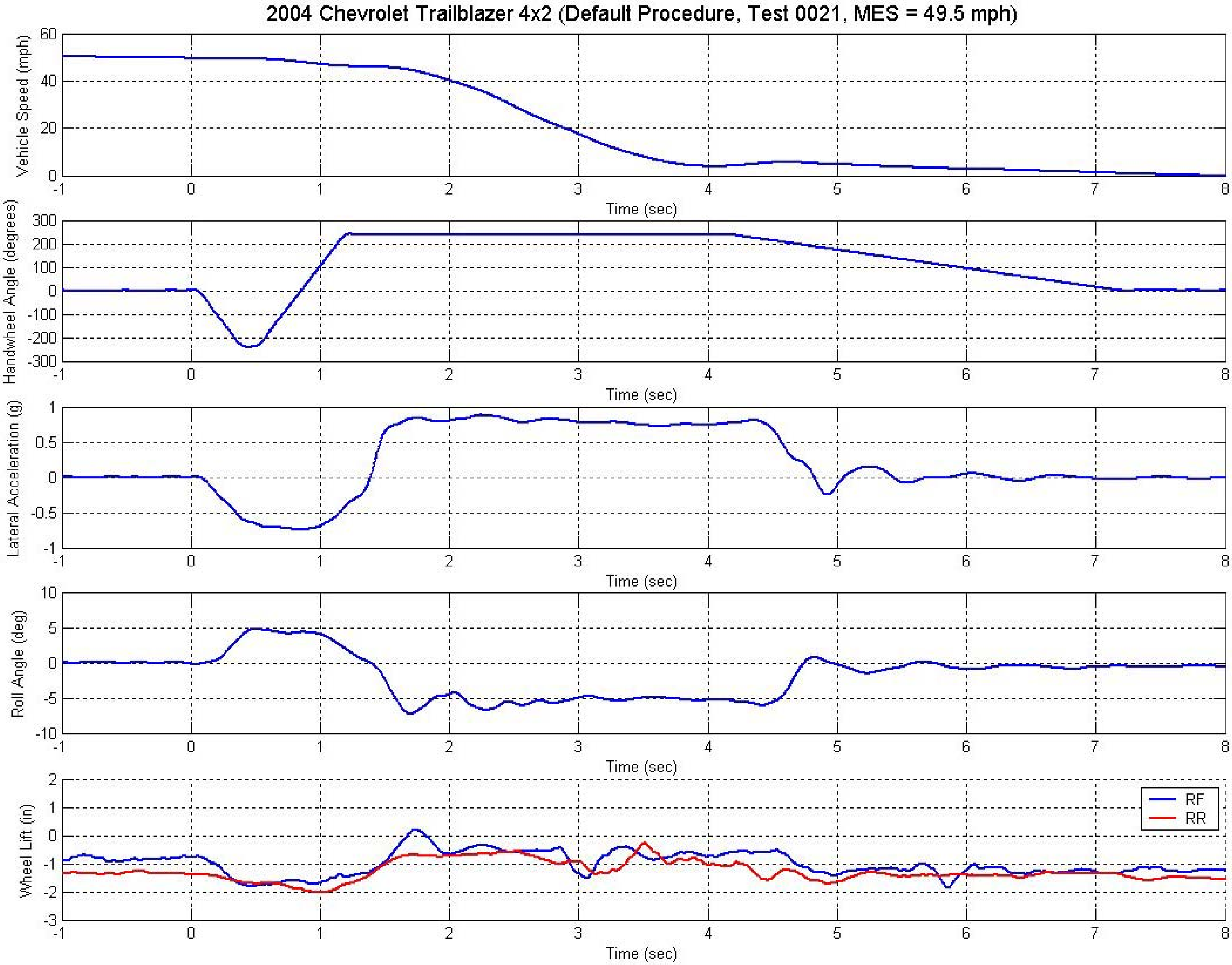

Figure A.13. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2004 Chevrolet Trailblazer 4x2.

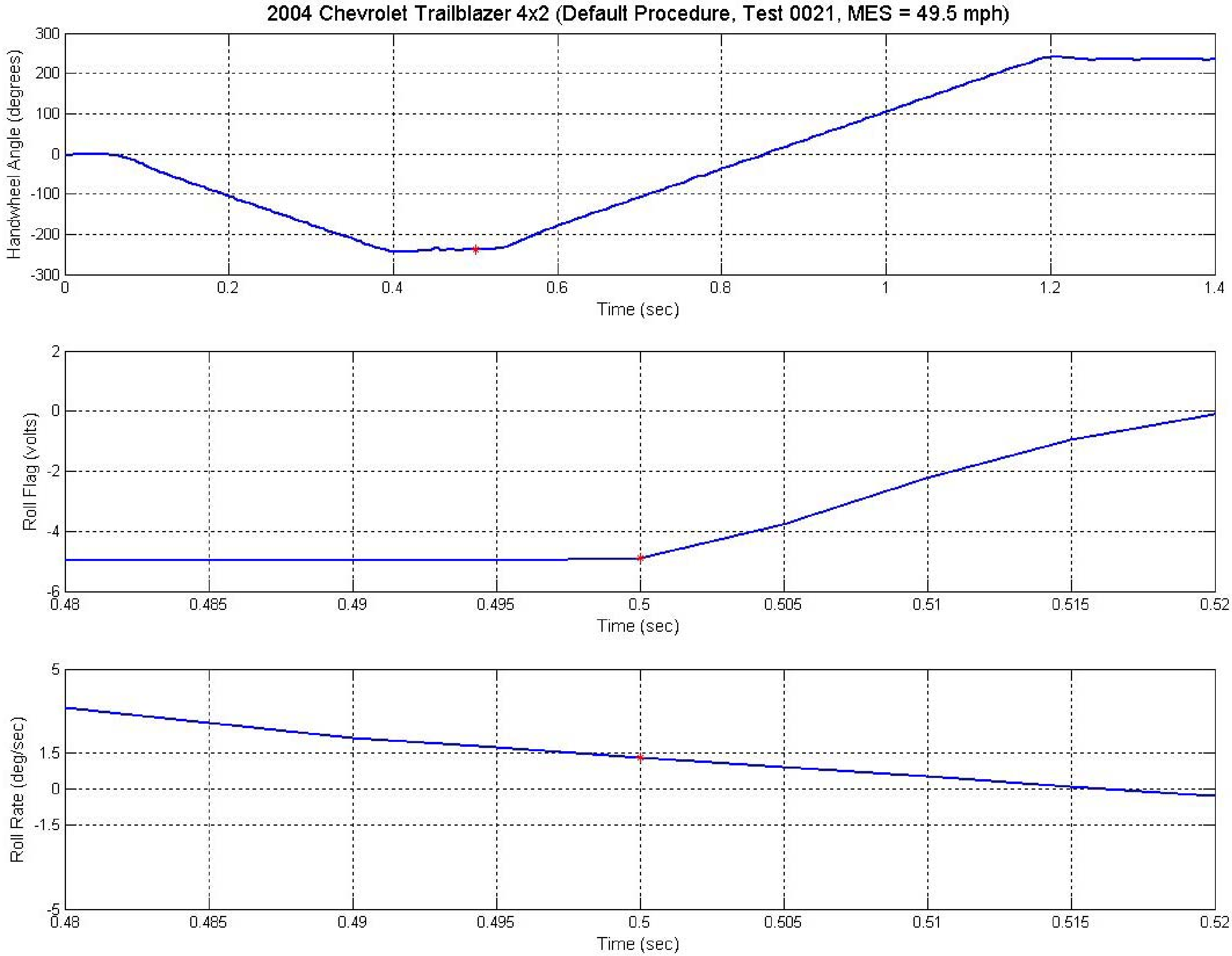

Figure A.14. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2004 Chevrolet Trailblazer 4x2.

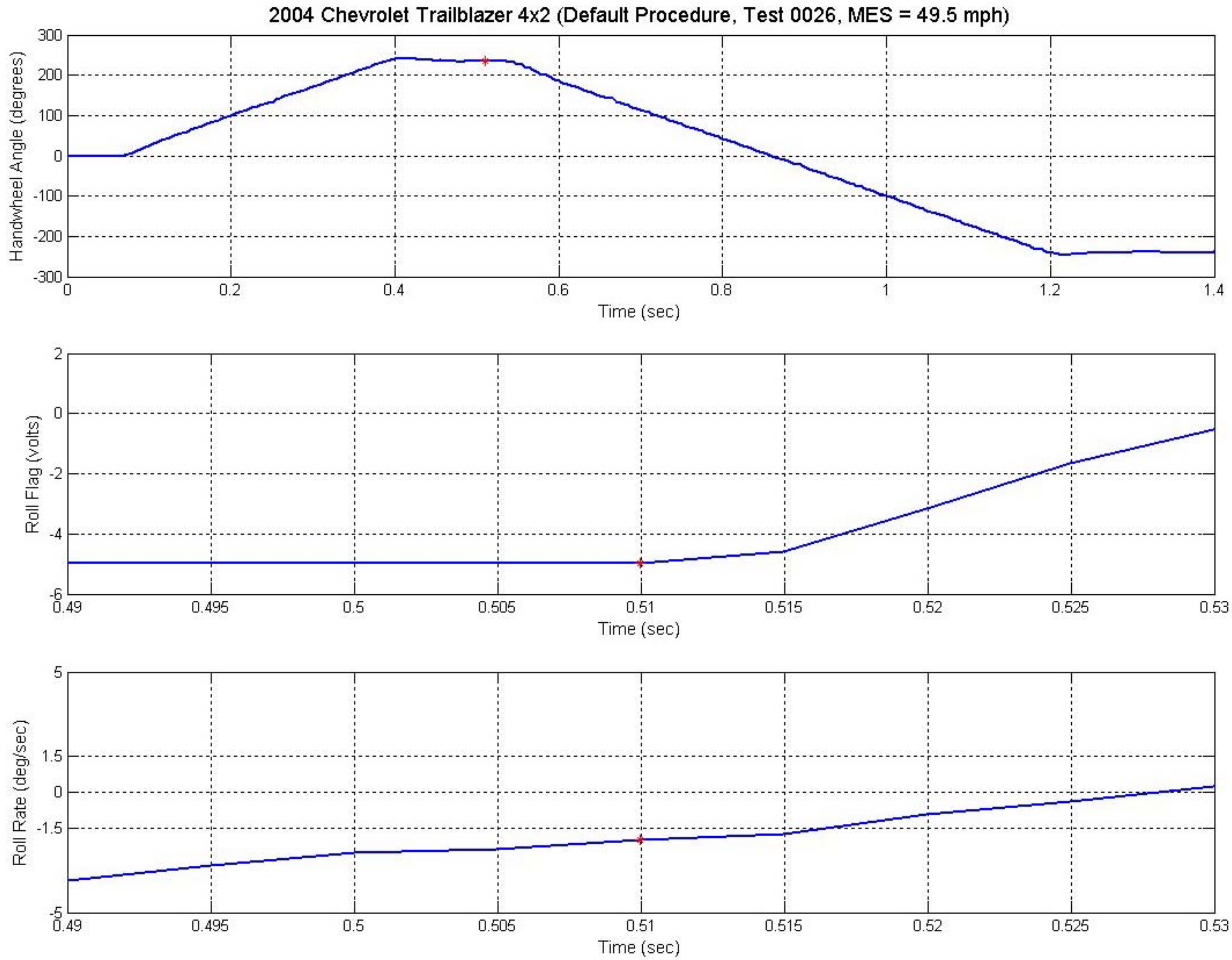

Figure A.15. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2004 Chevrolet Trailblazer 4x2.

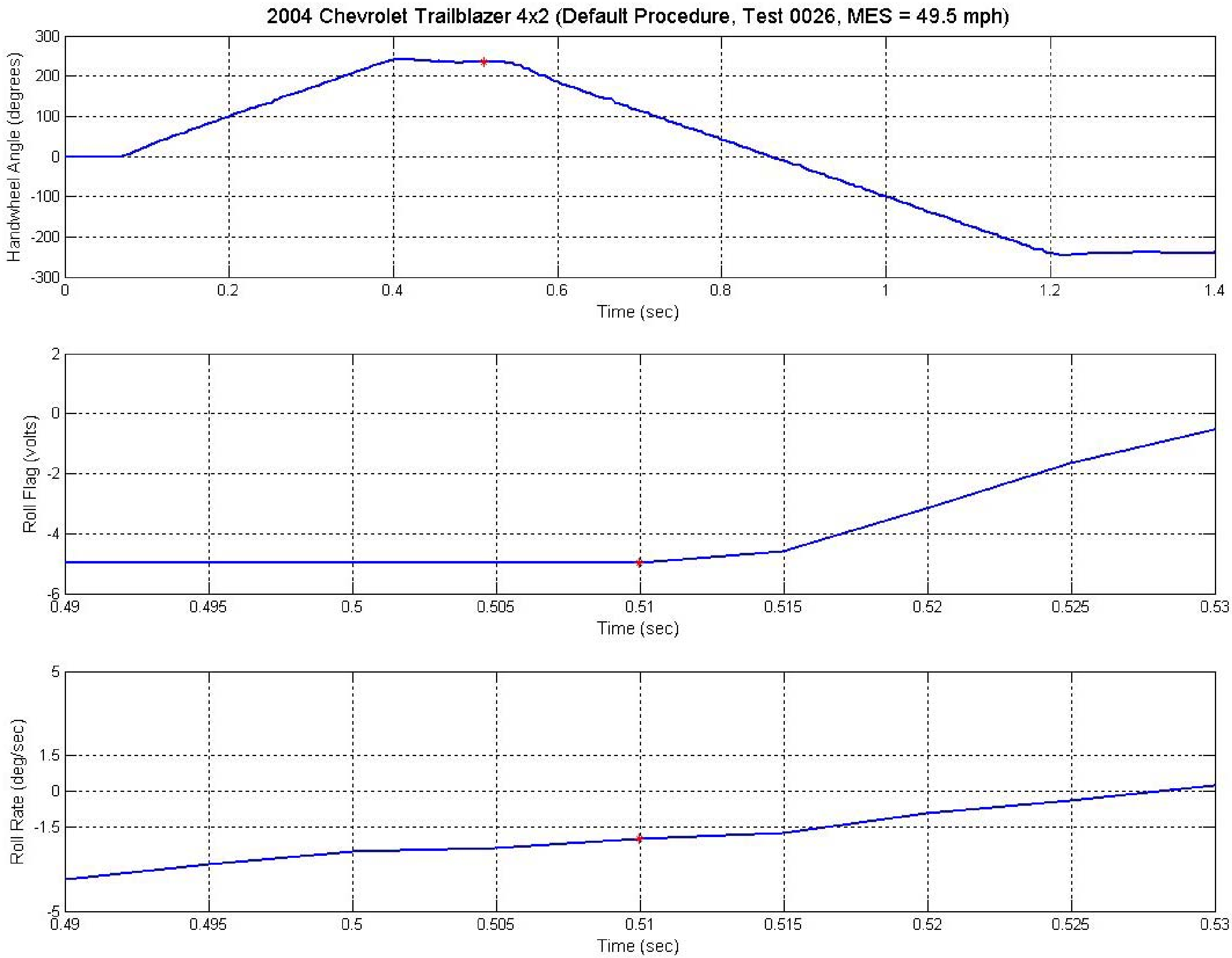

Figure A.16. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2004 Chevrolet Trailblazer 4x2.

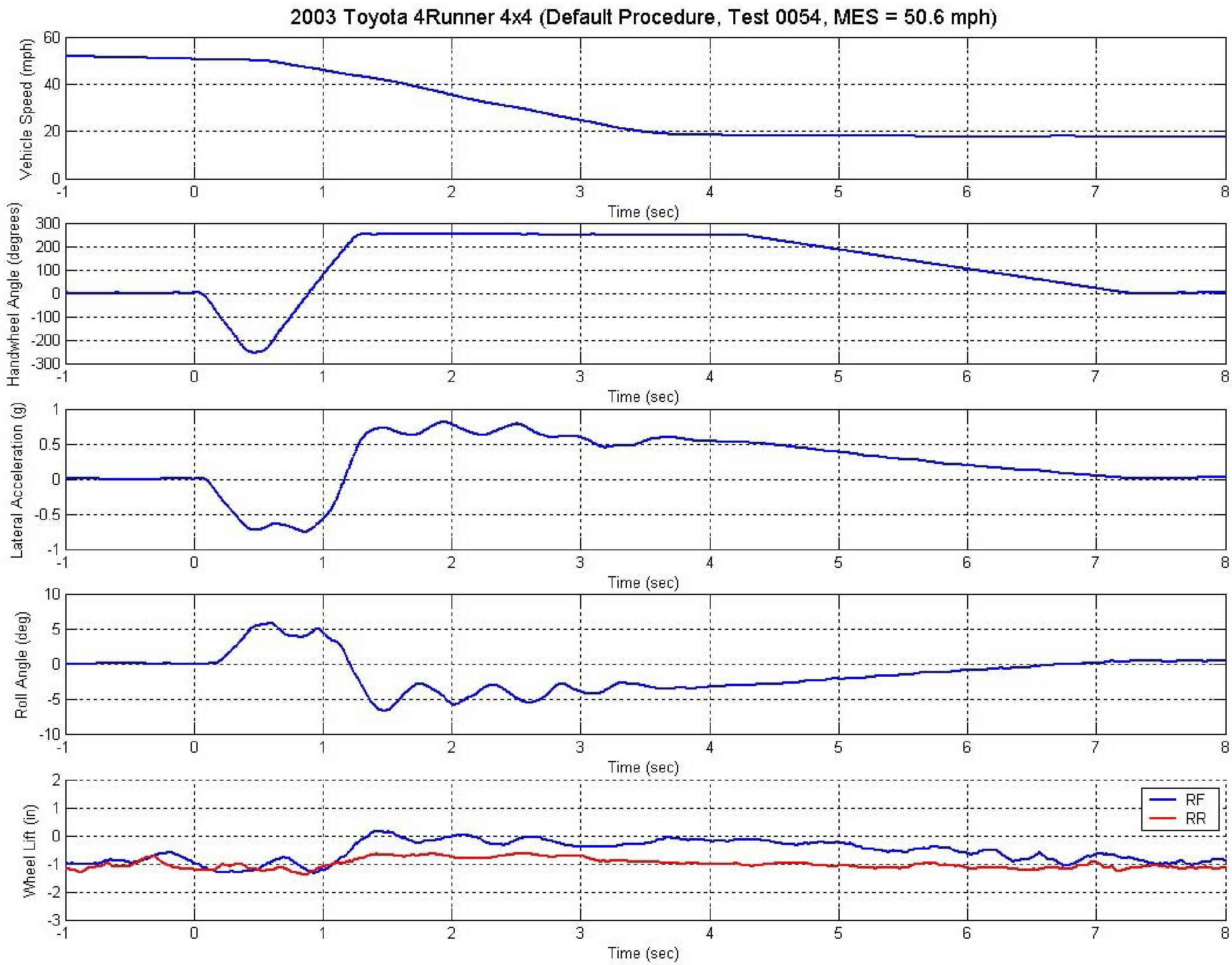

Figure A.17. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Toyota 4Runner 4x4.

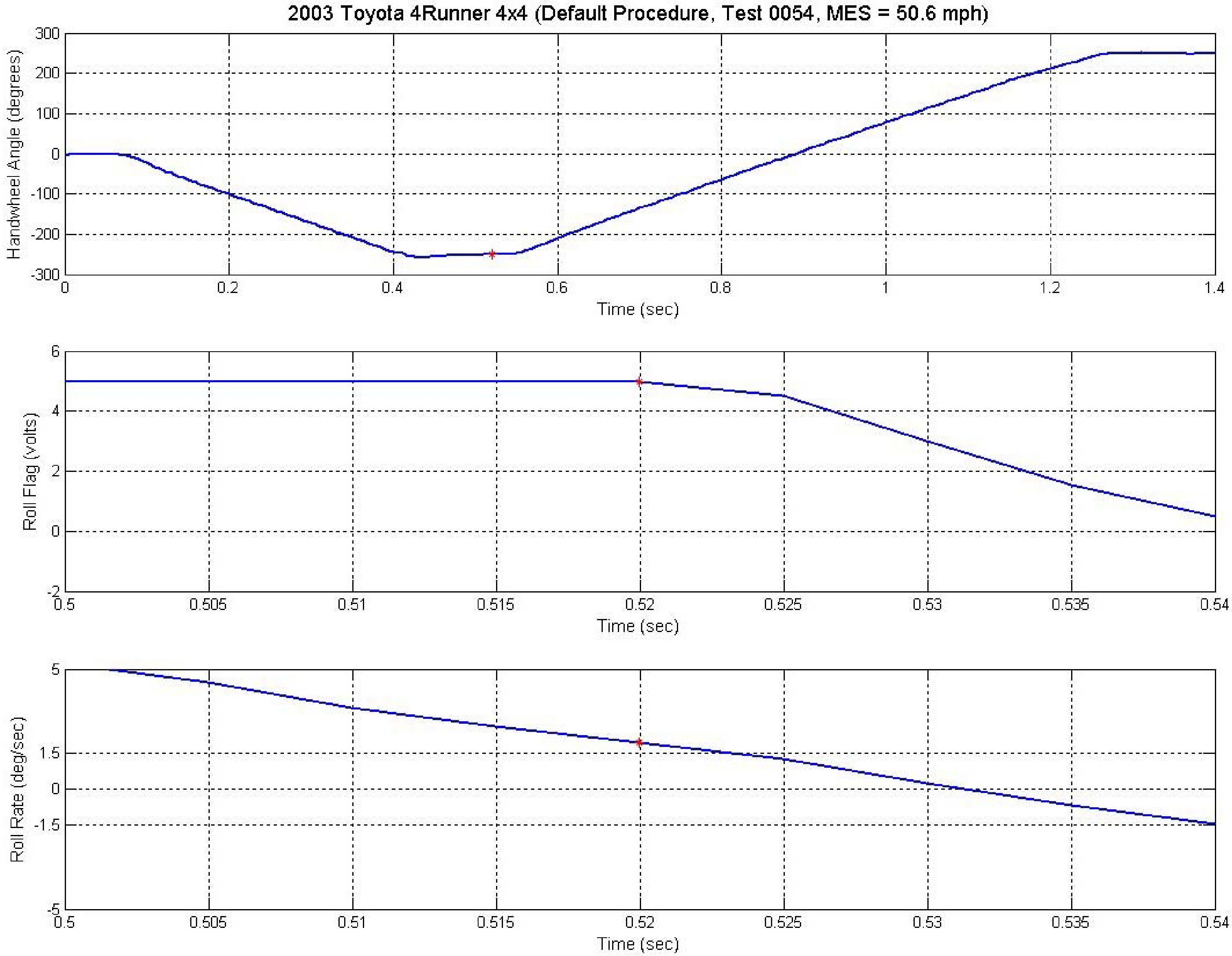

Figure A.18. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Toyota 4Runner 4x4.

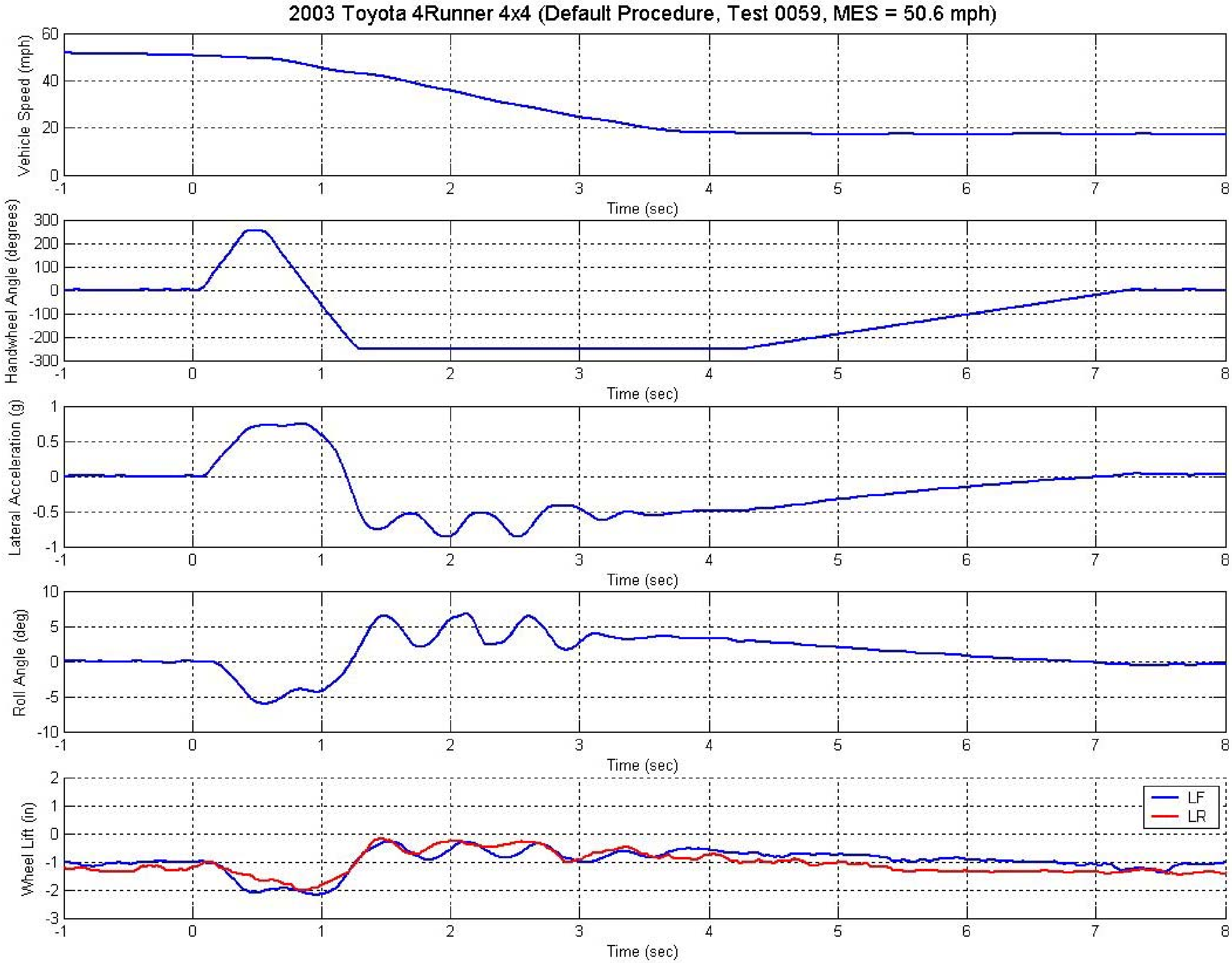

Figure A.19. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Toyota 4Runner 4x4.

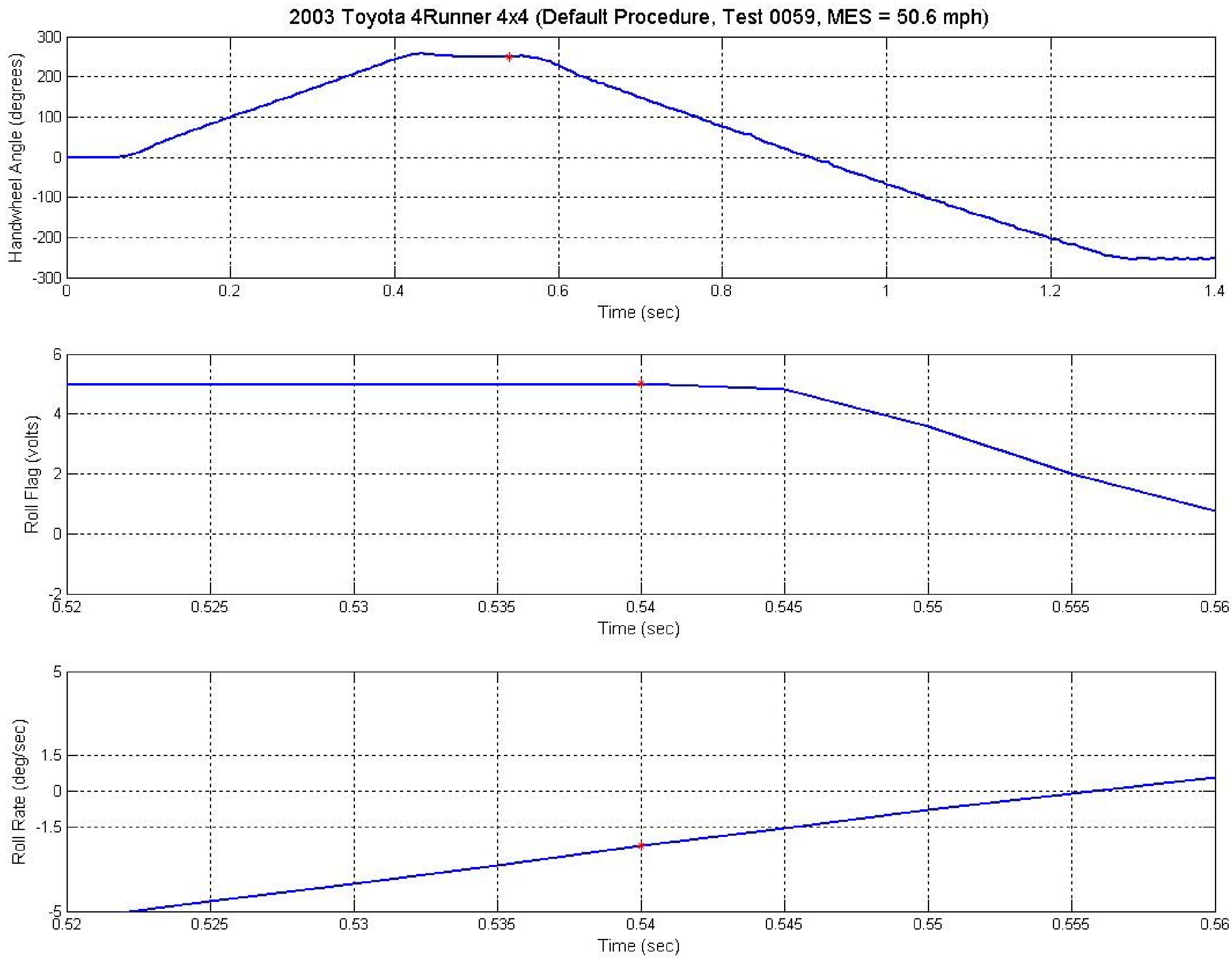

Figure A.20. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Toyota 4Runner 4x4.

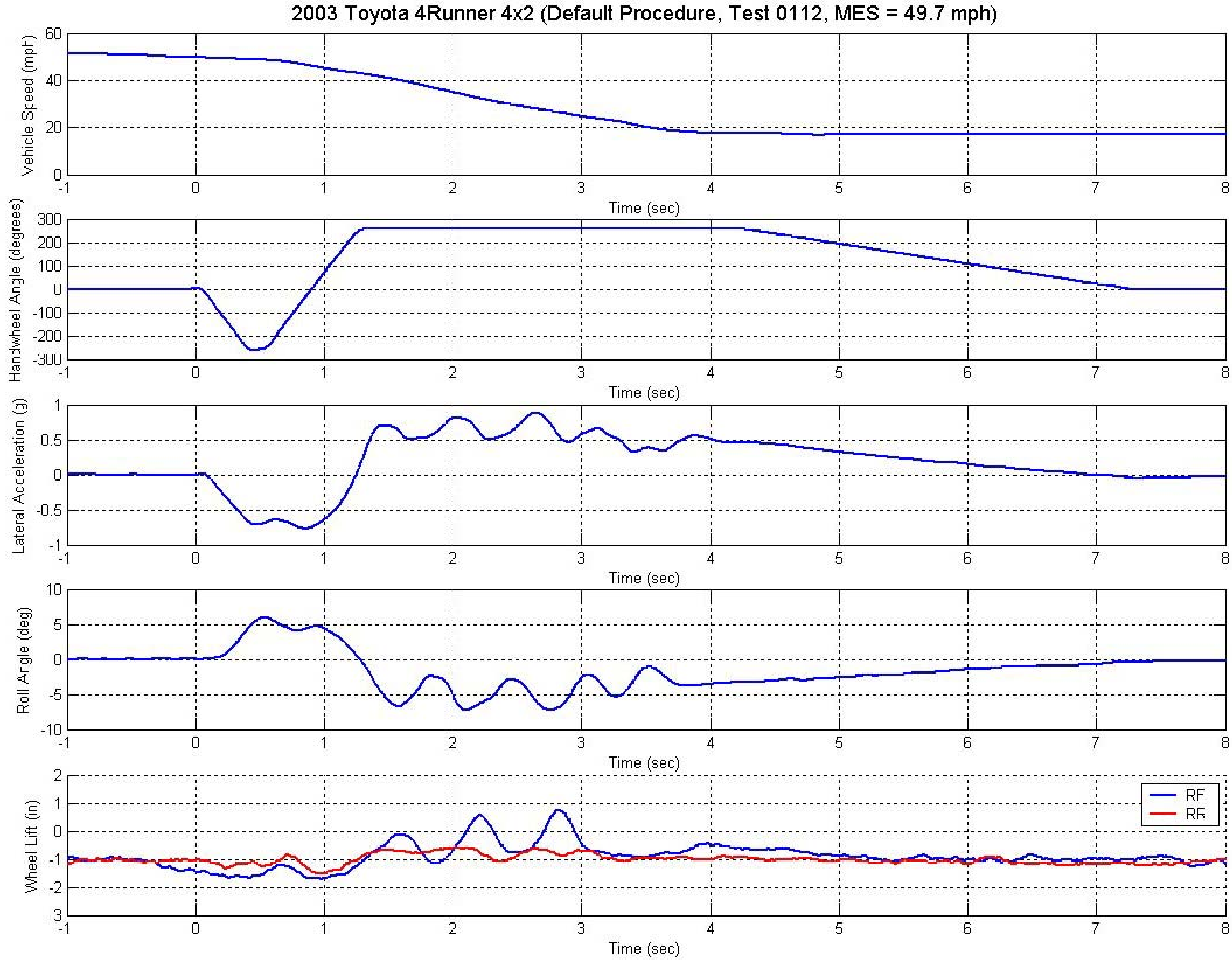

Figure A.21. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Toyota 4Runner 4x2.

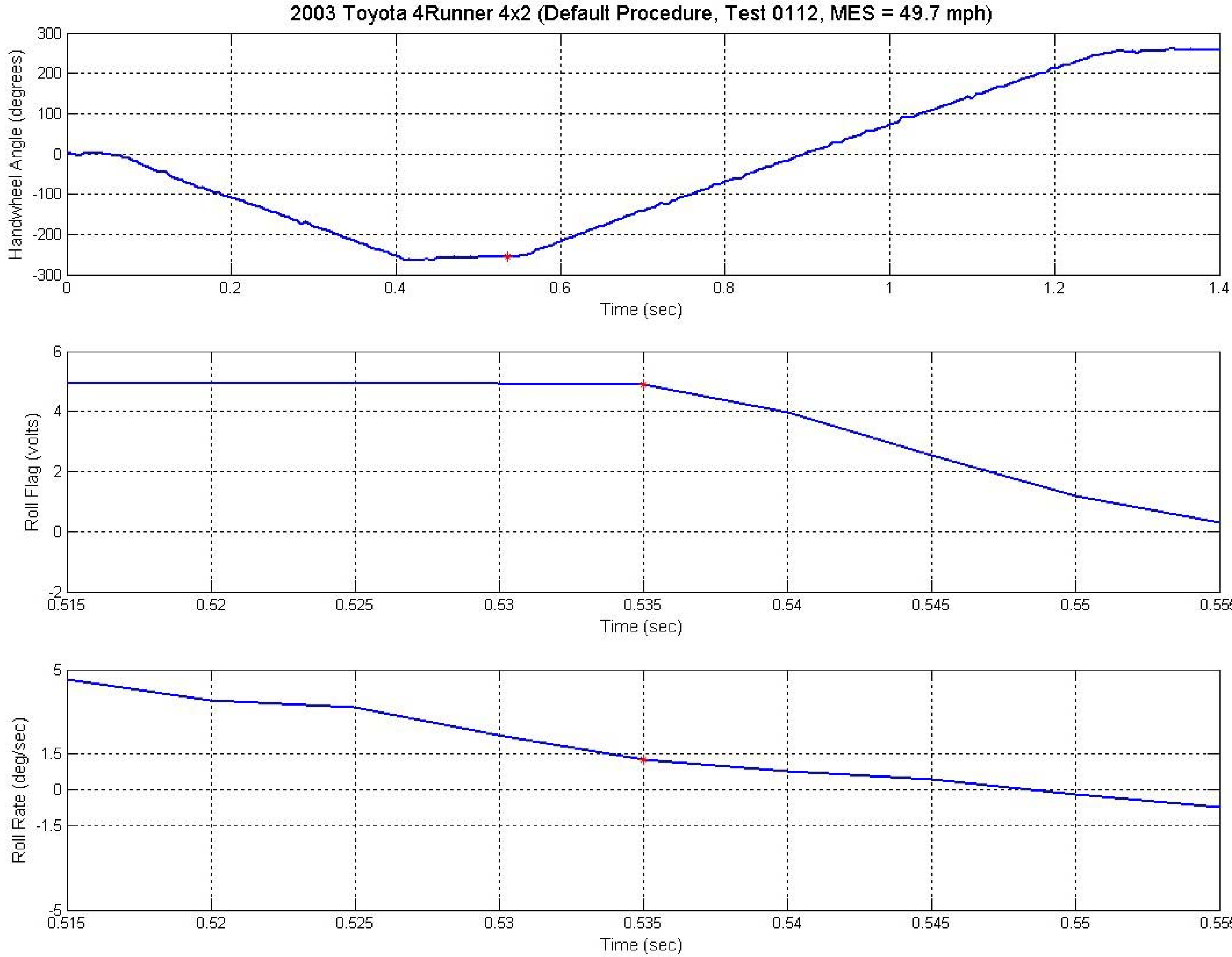

Figure A.22. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Toyota 4Runner 4x2.

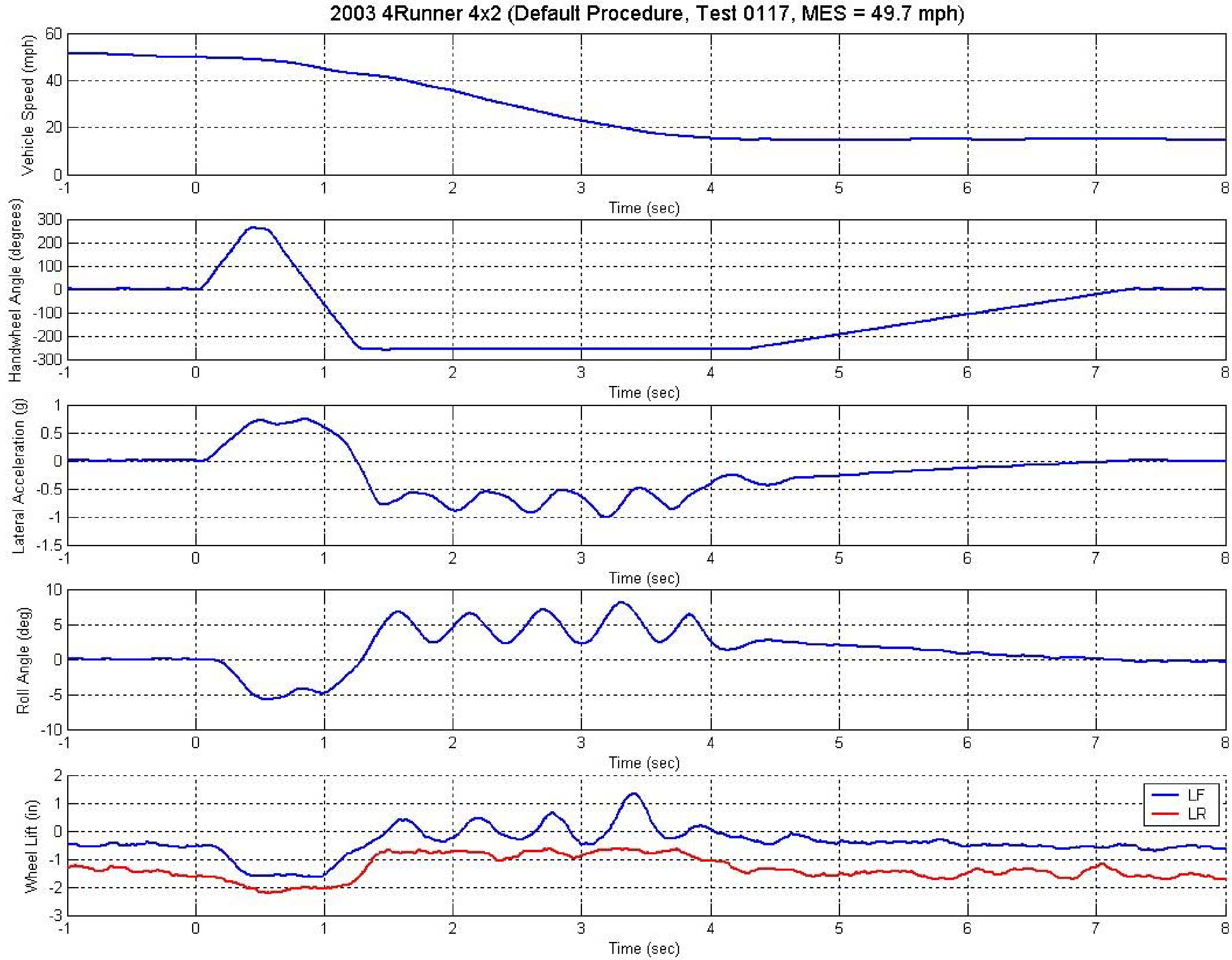

Figure A.23. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Toyota 4Runner 4x2.

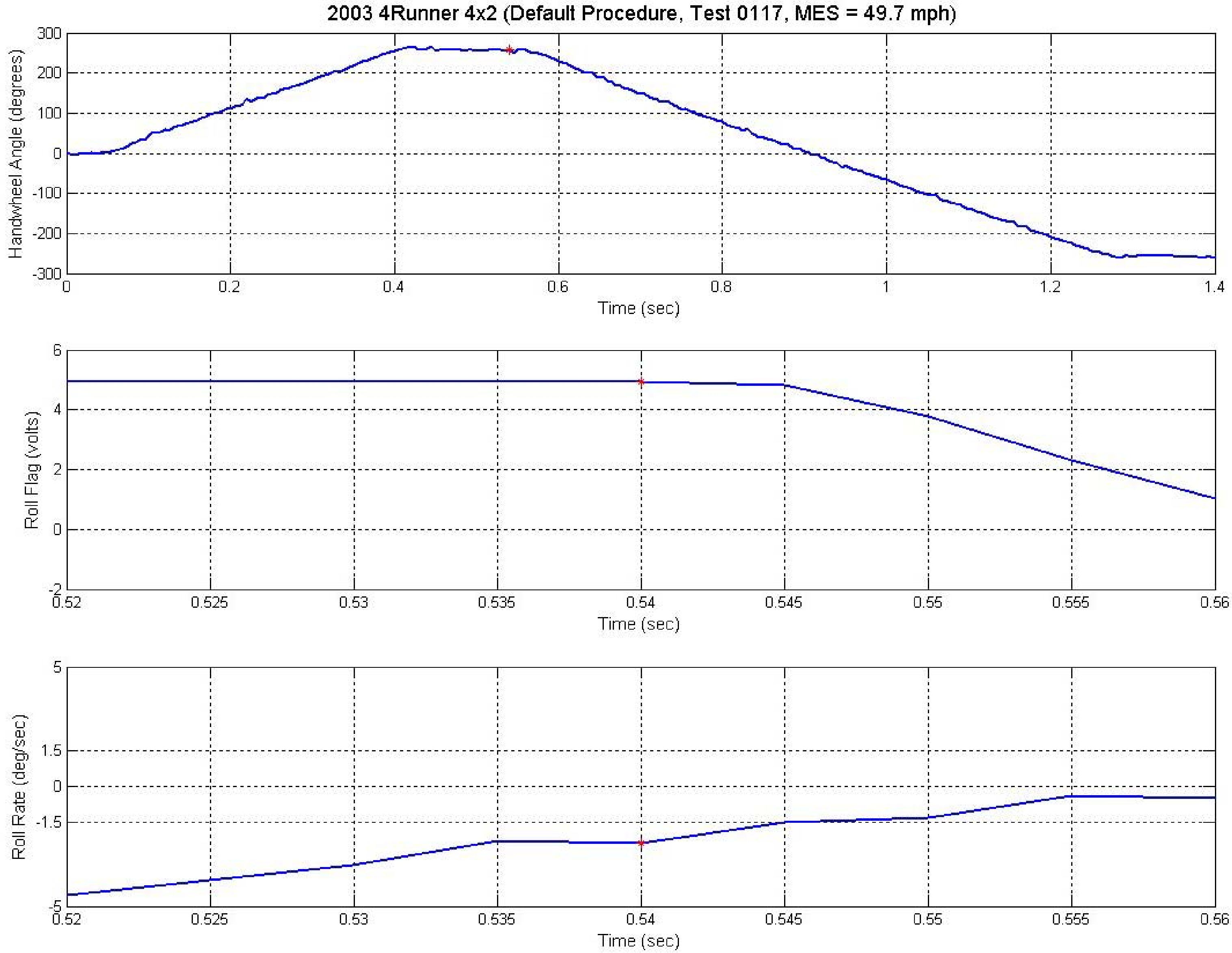

Figure A.24. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Toyota 4Runner 4x2.

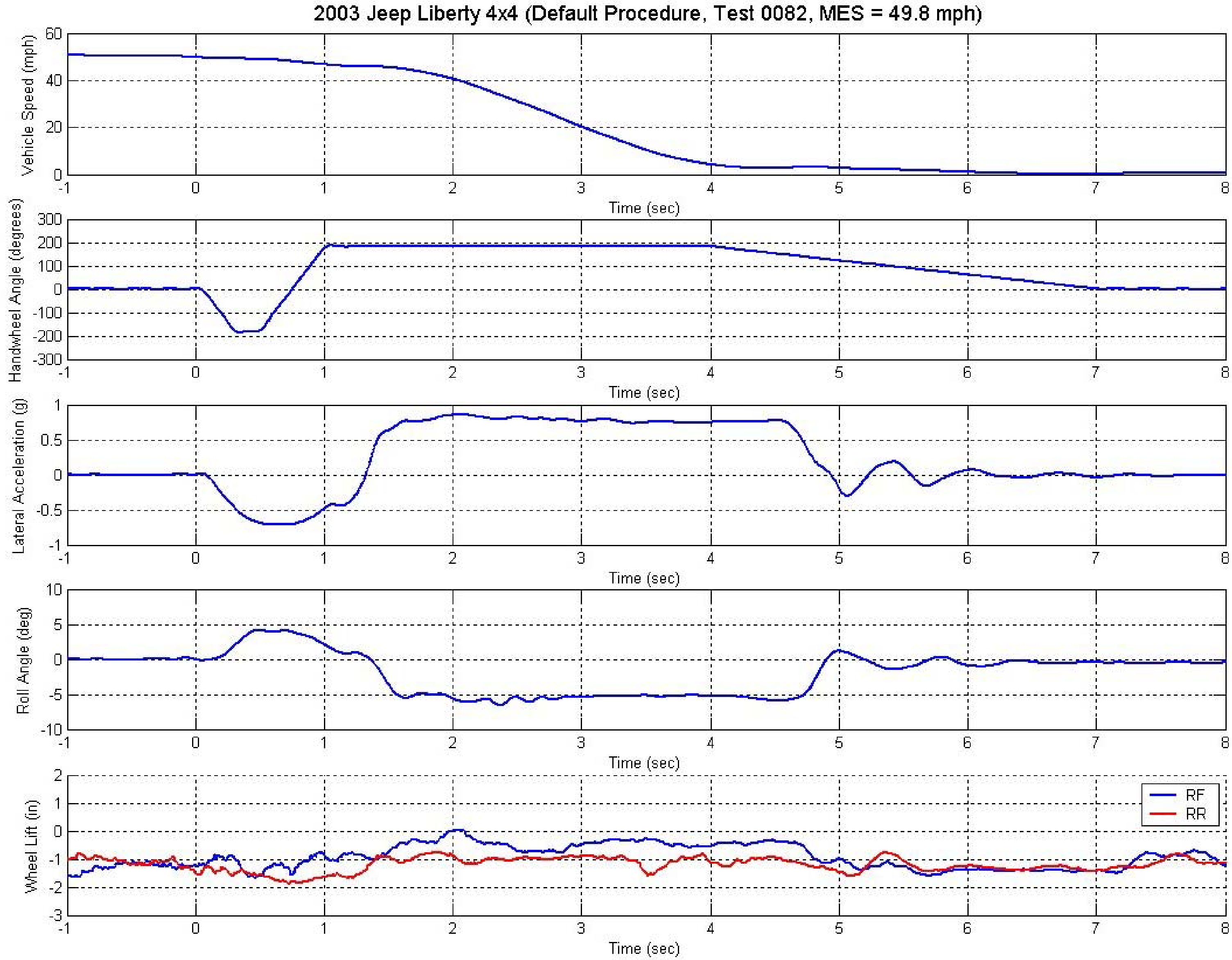

Figure A.25. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Jeep Liberty 4x4.

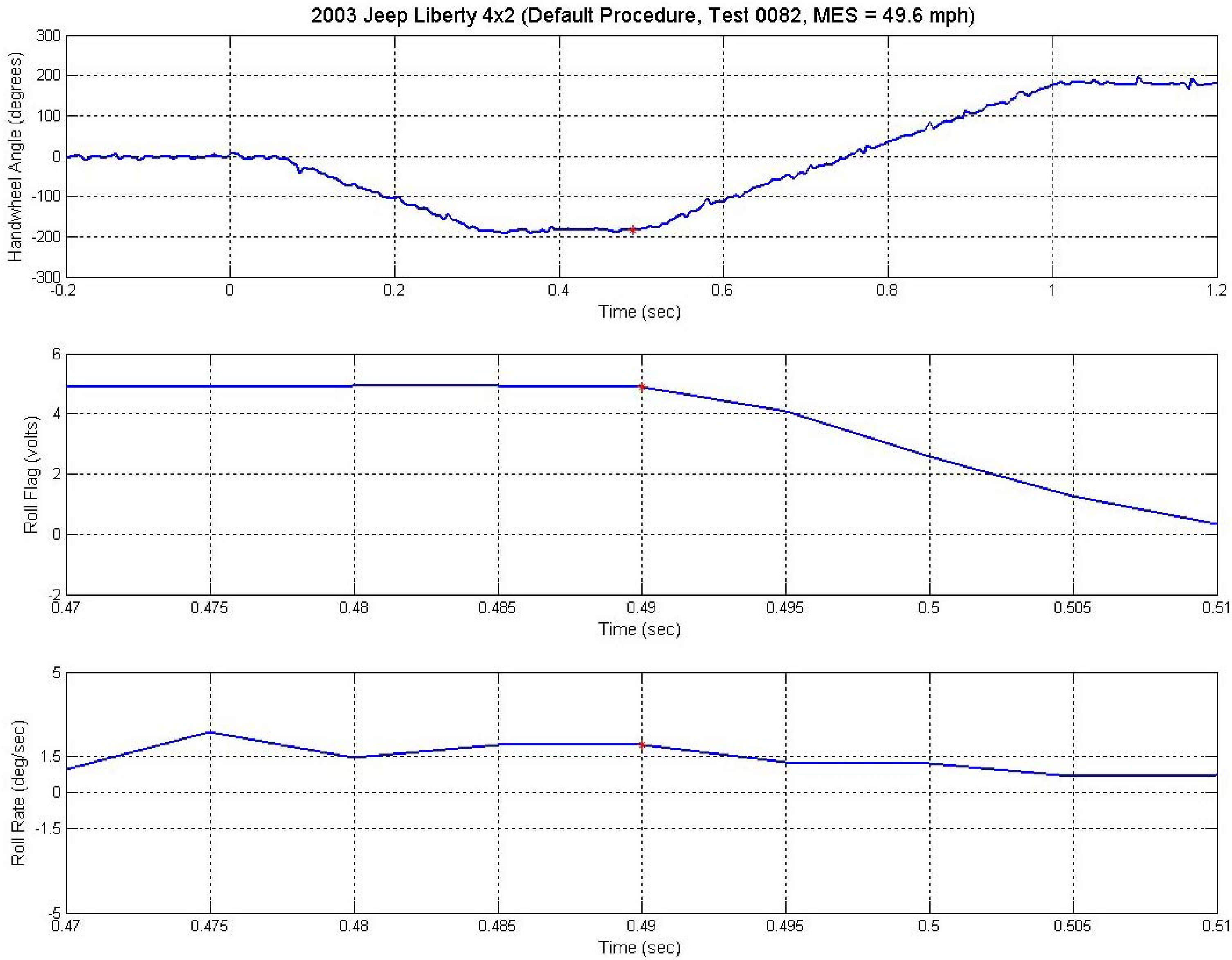

Figure A.26. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Jeep Liberty 4x4.

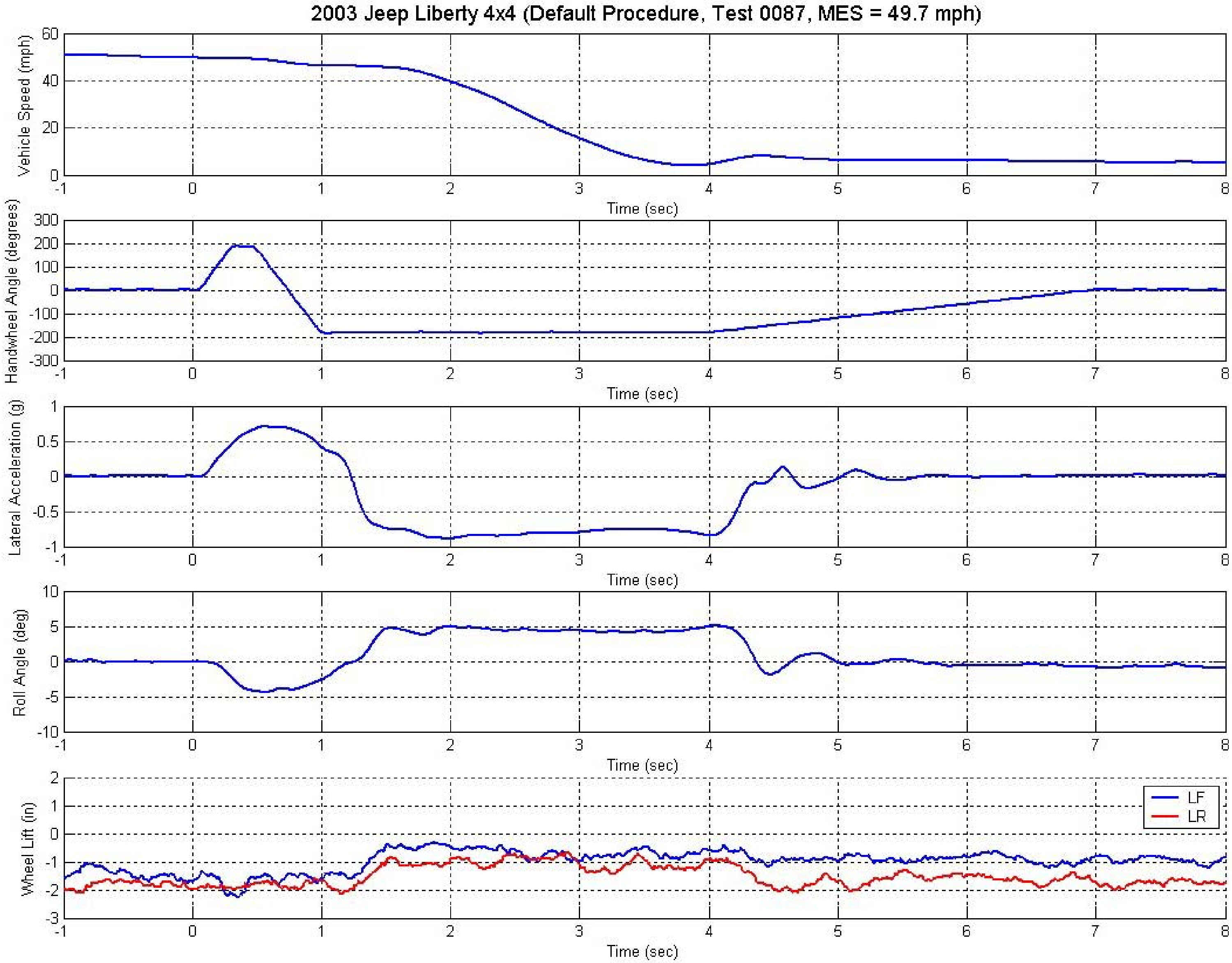

Figure A.27. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Jeep Liberty 4x4.

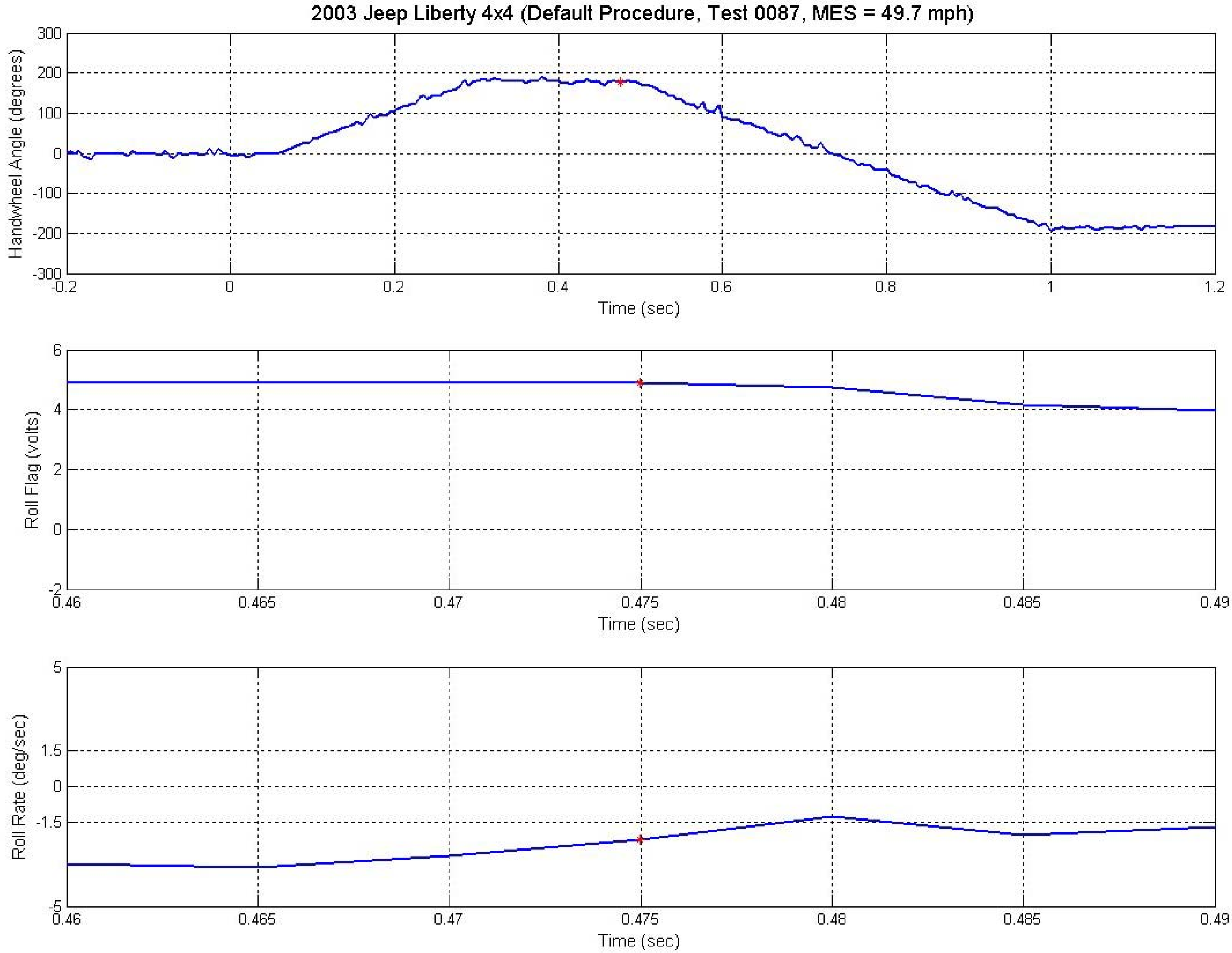

Figure A.28. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Jeep Liberty 4x4.

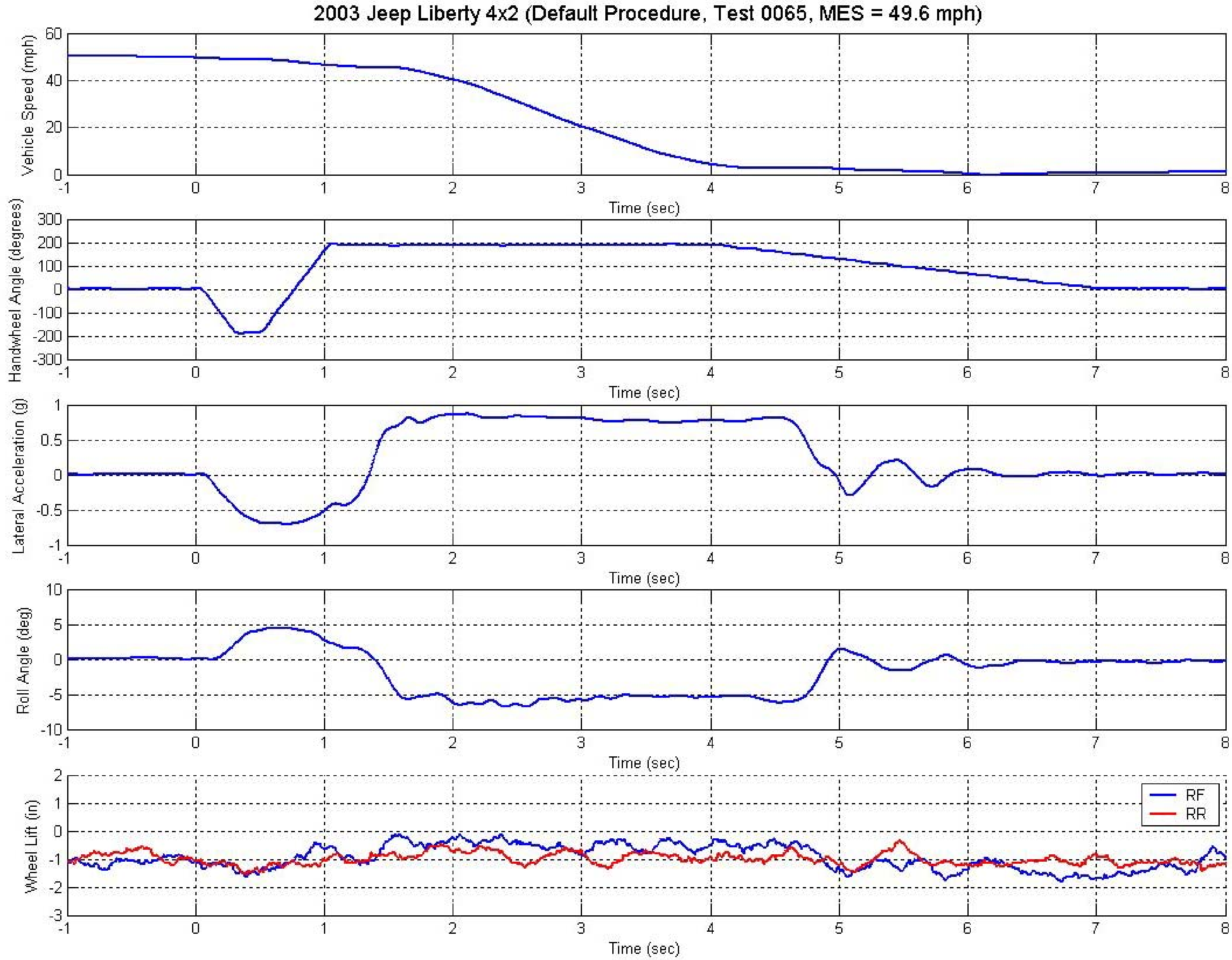

Figure A.29. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Road Edge Recovery maneuver – 2003 Jeep Liberty 4x2.

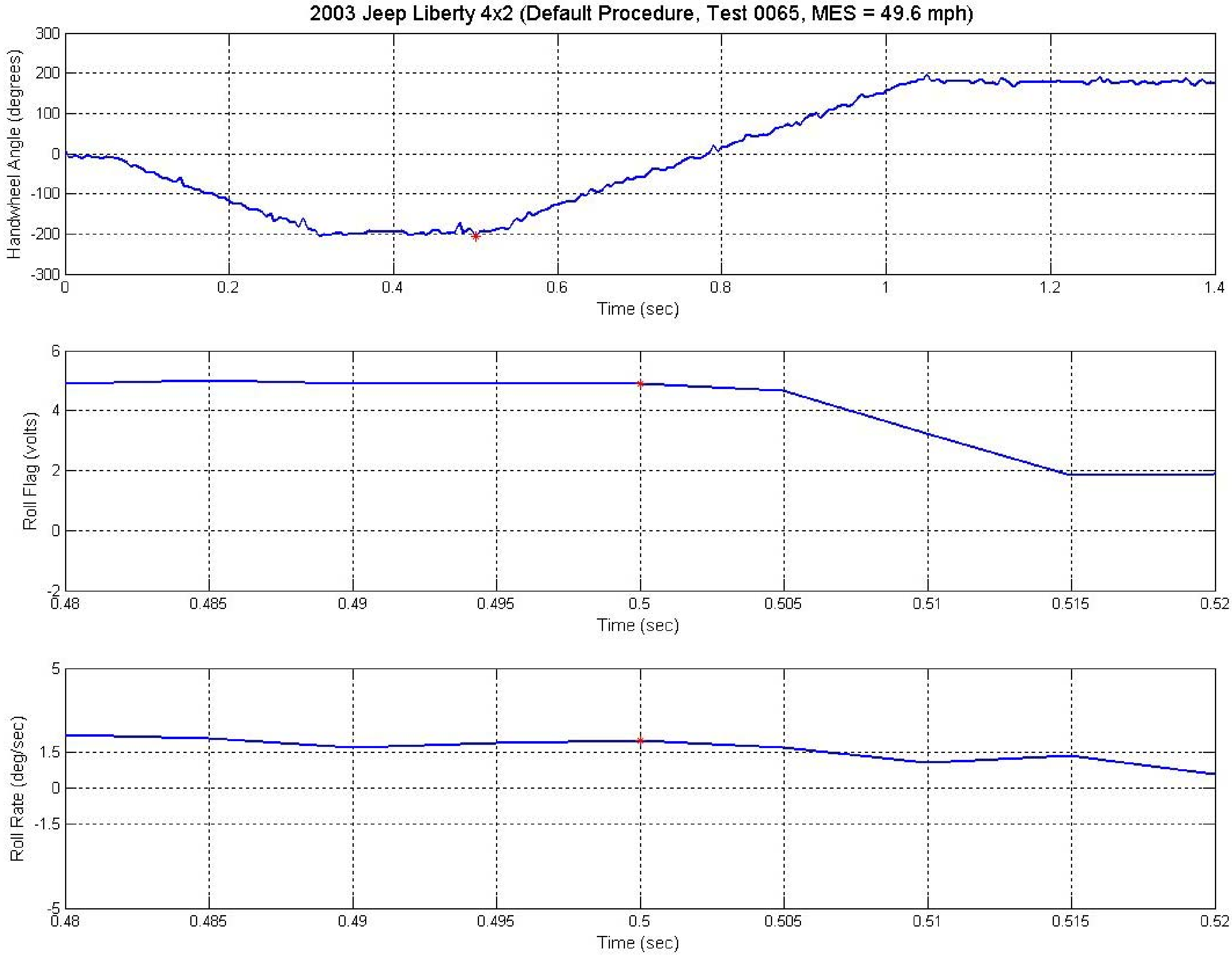

Figure A.30. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Jeep Liberty 4x2.

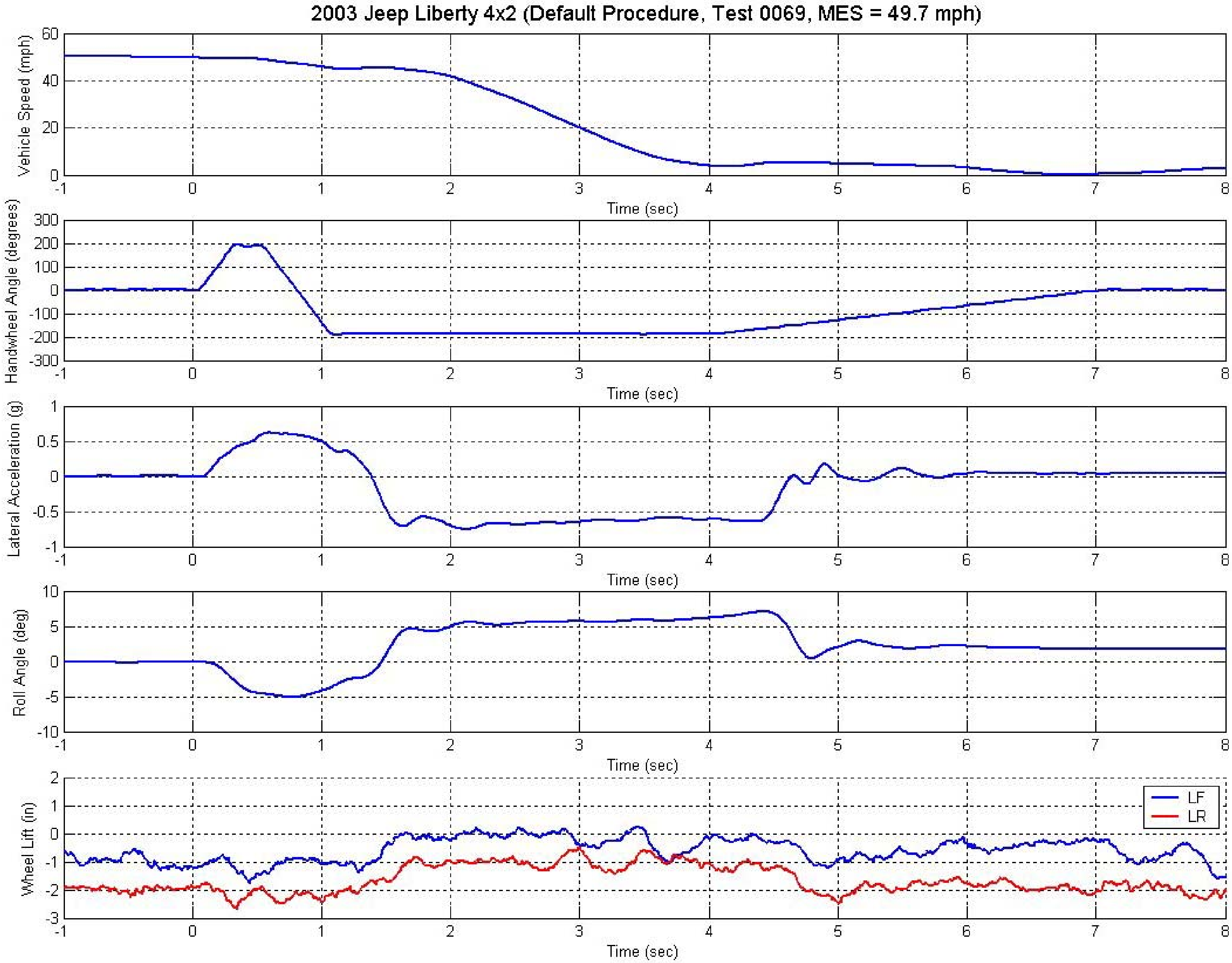

Figure A.31. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Jeep Liberty 4x2.

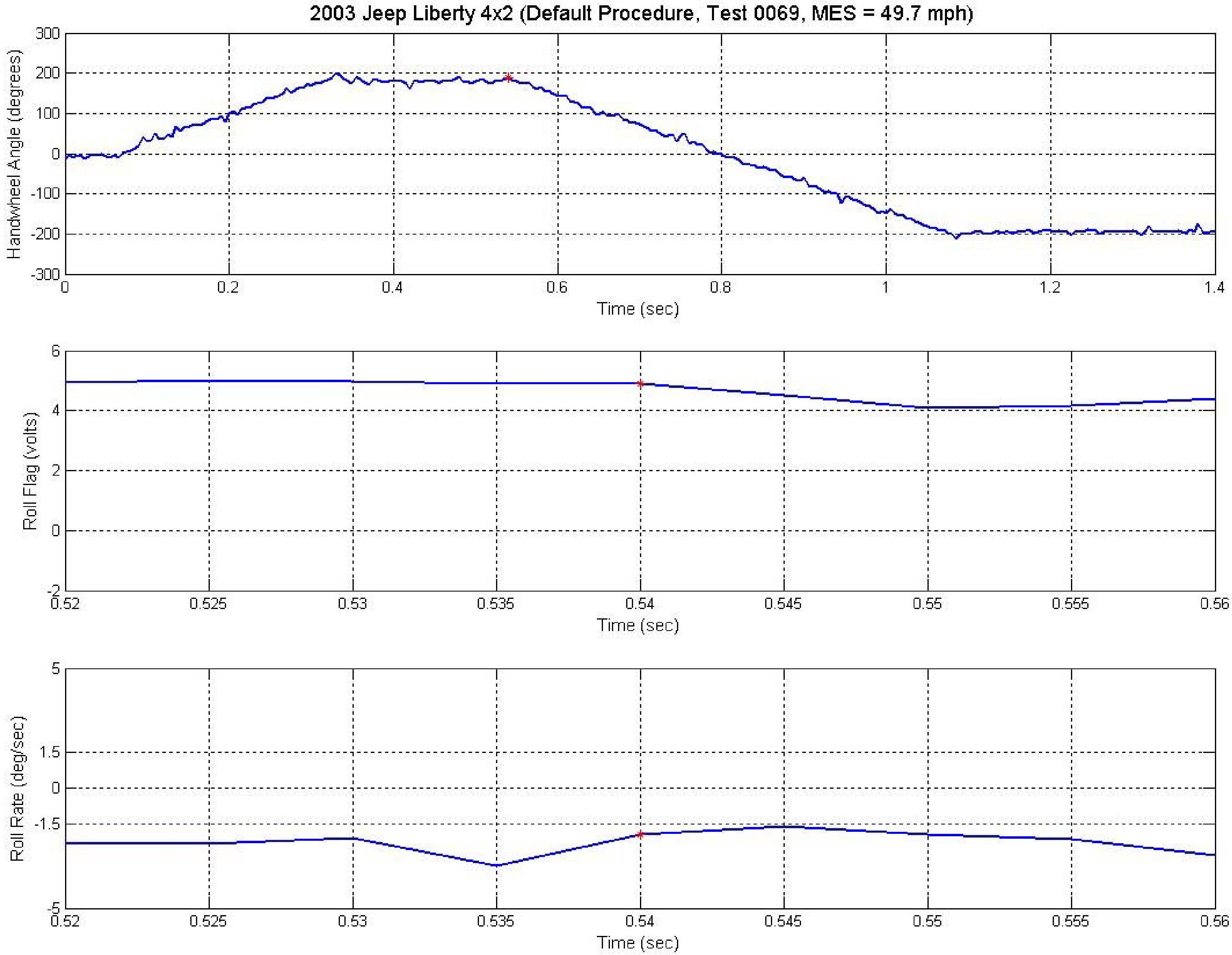

Figure A.32. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Jeep Liberty 4x2.

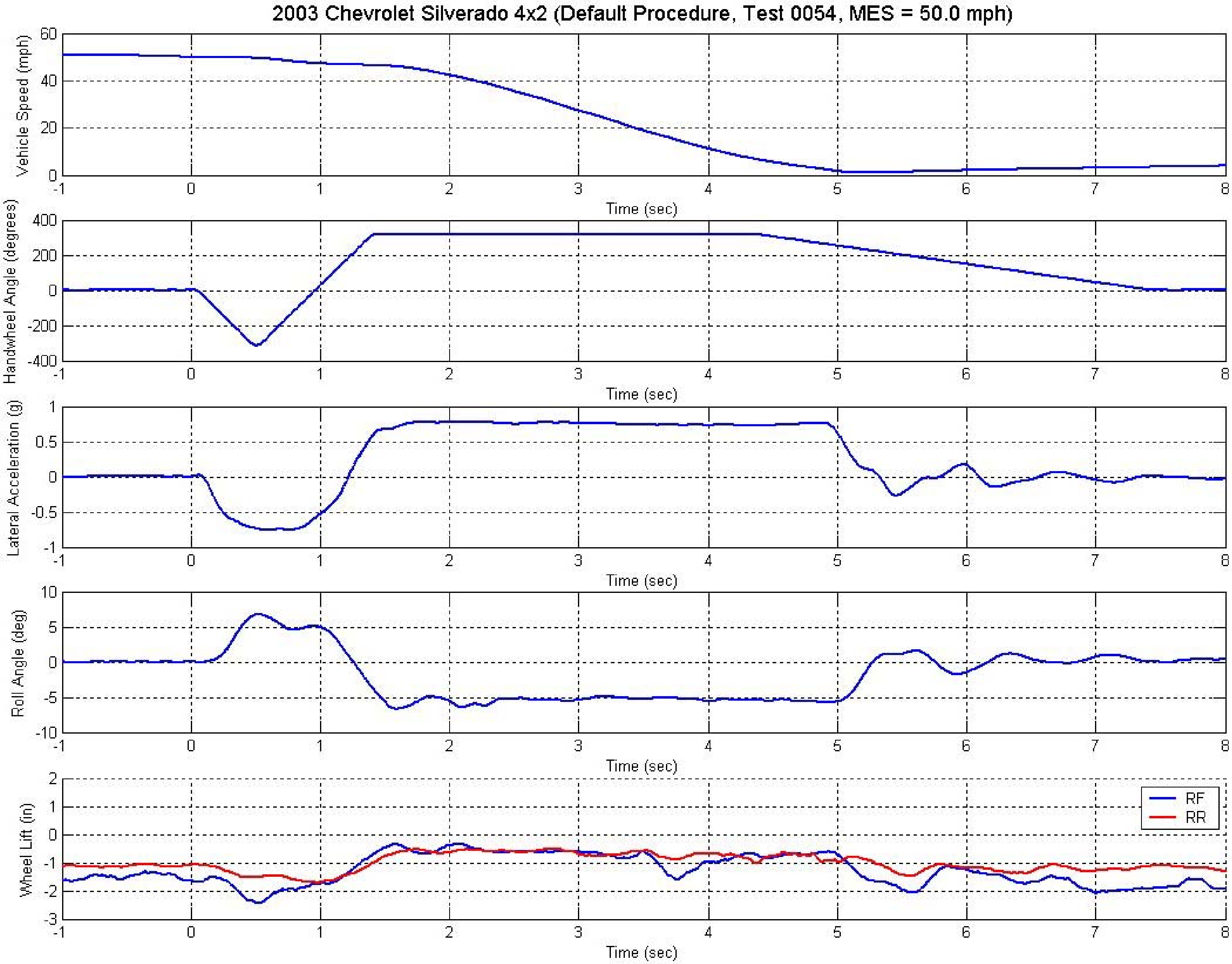

Figure A.33. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Chevrolet Silverado 4x2.

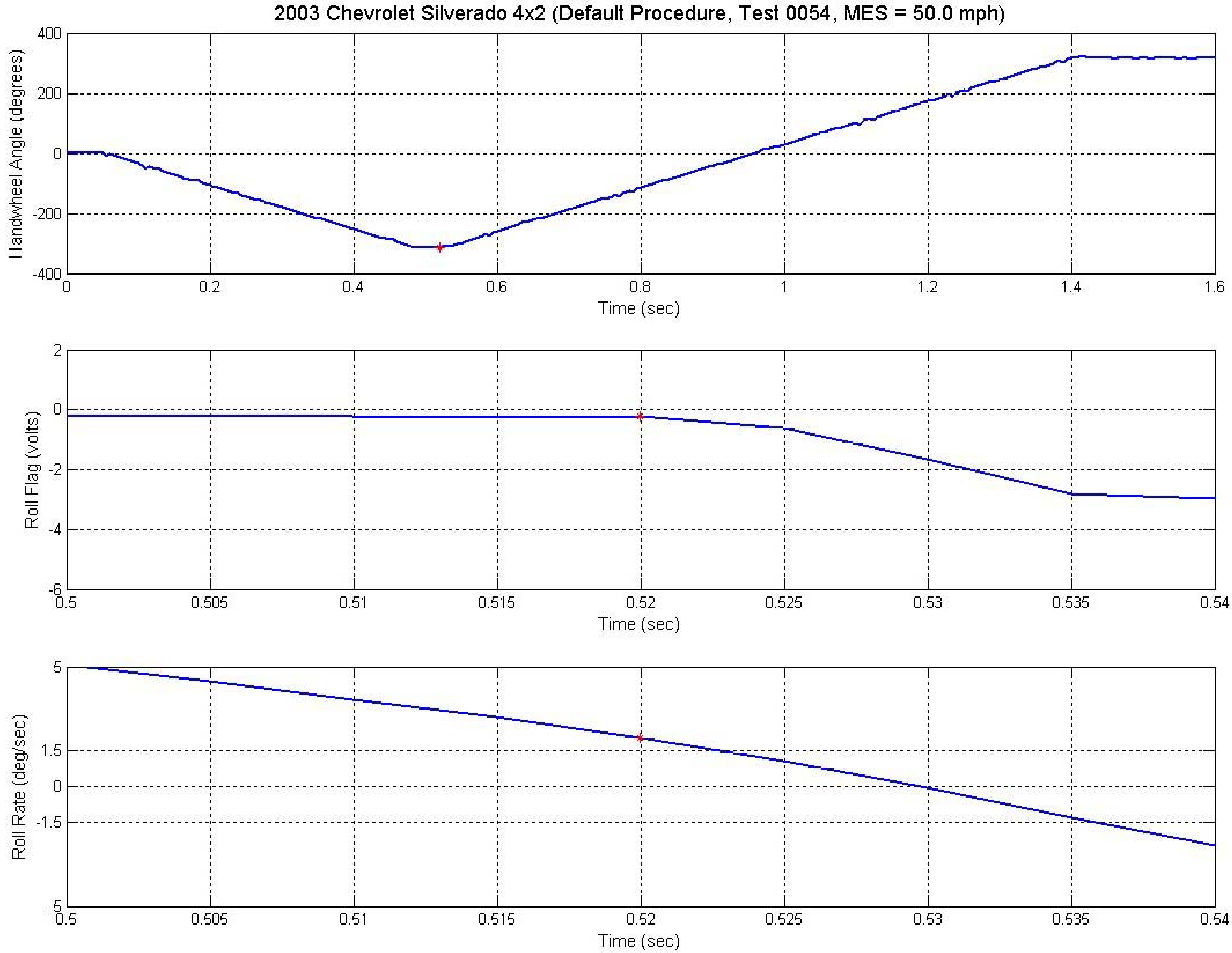

Figure A.34. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Chevrolet Silverado 4x2.

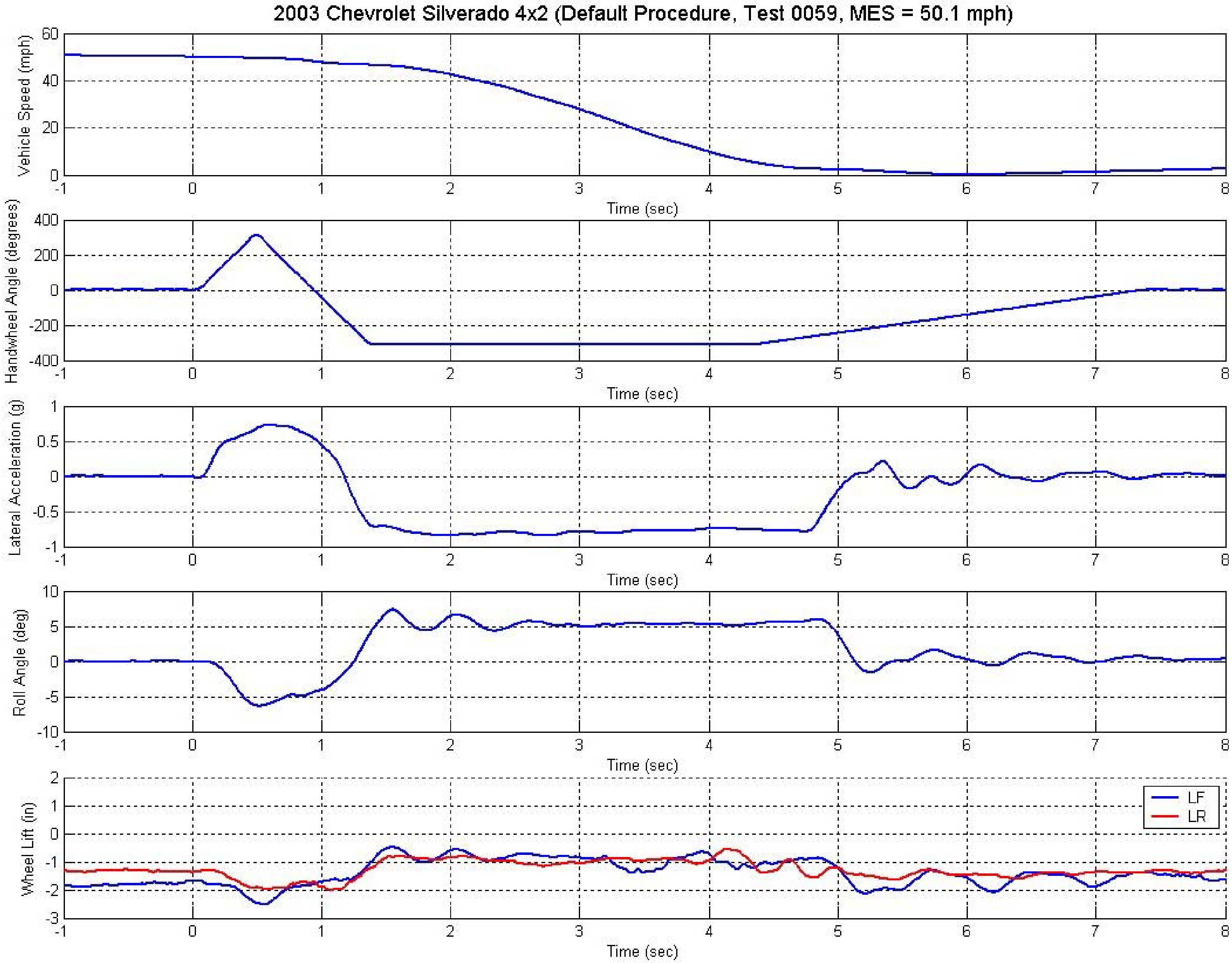

Figure A.35. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Chevrolet Silverado 4x2.

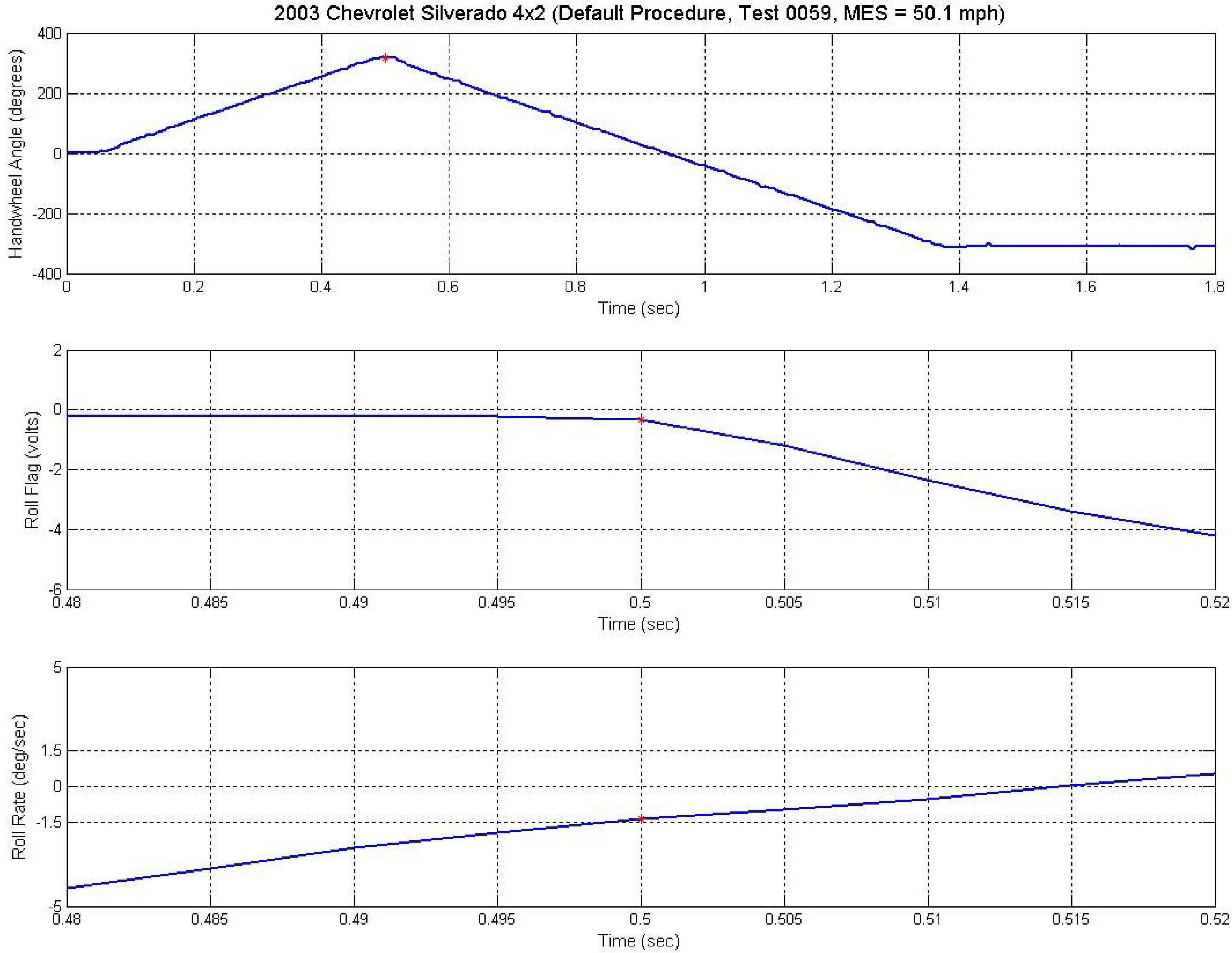

Figure A.36. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Chevrolet Silverado 4x2.

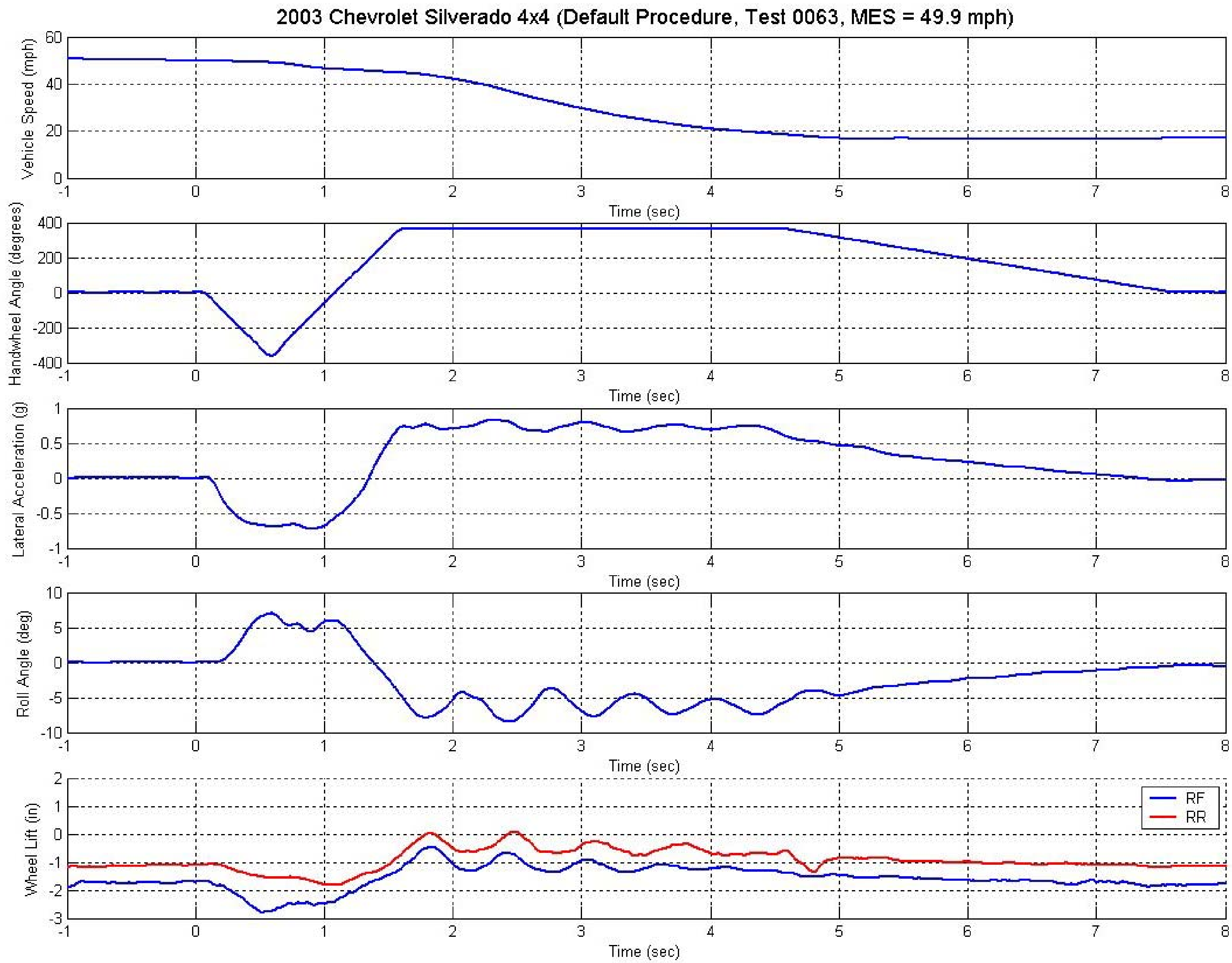

Figure A.37. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Chevrolet Silverado 4x4.

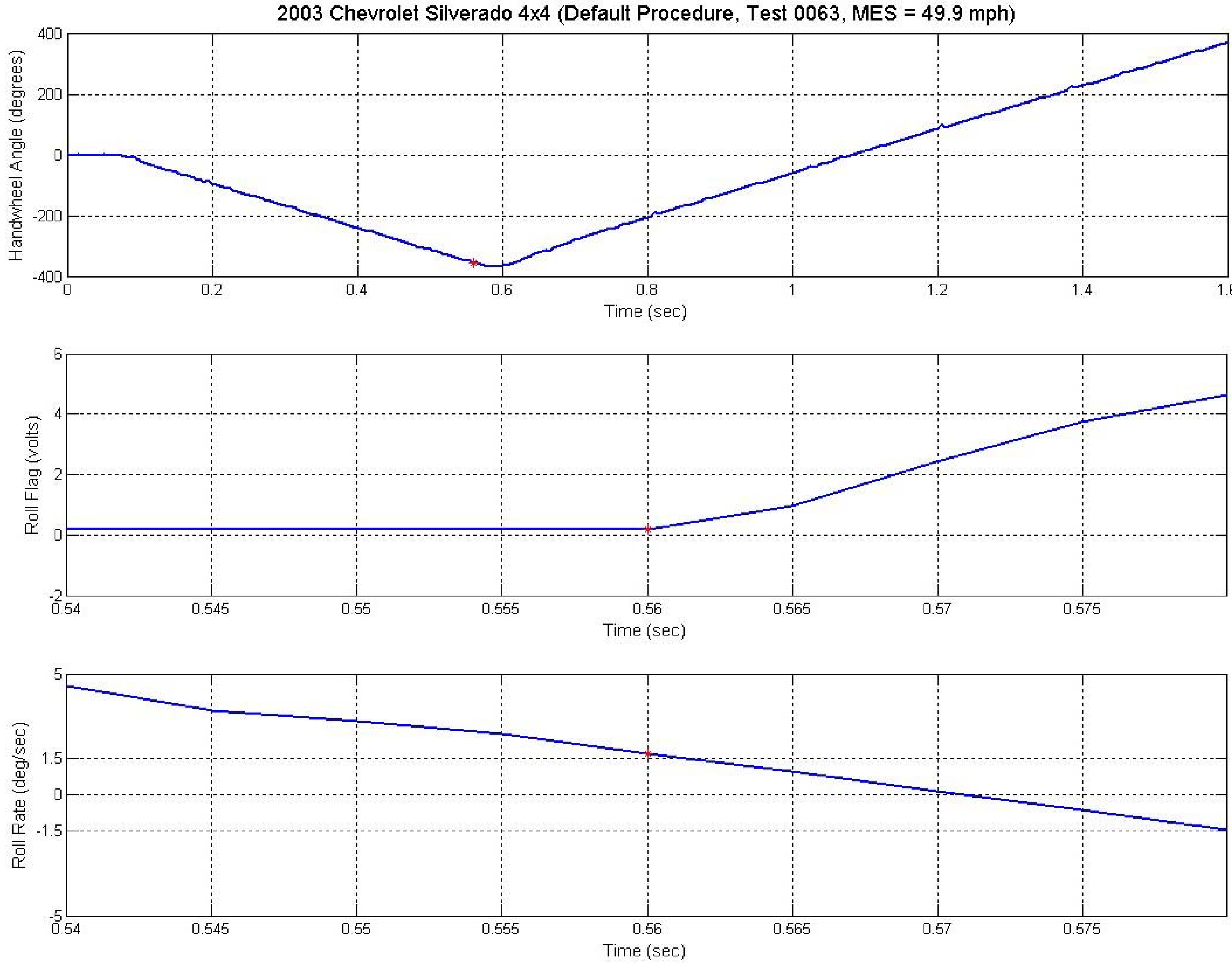

Figure A.38. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Chevrolet Silverado 4x4.

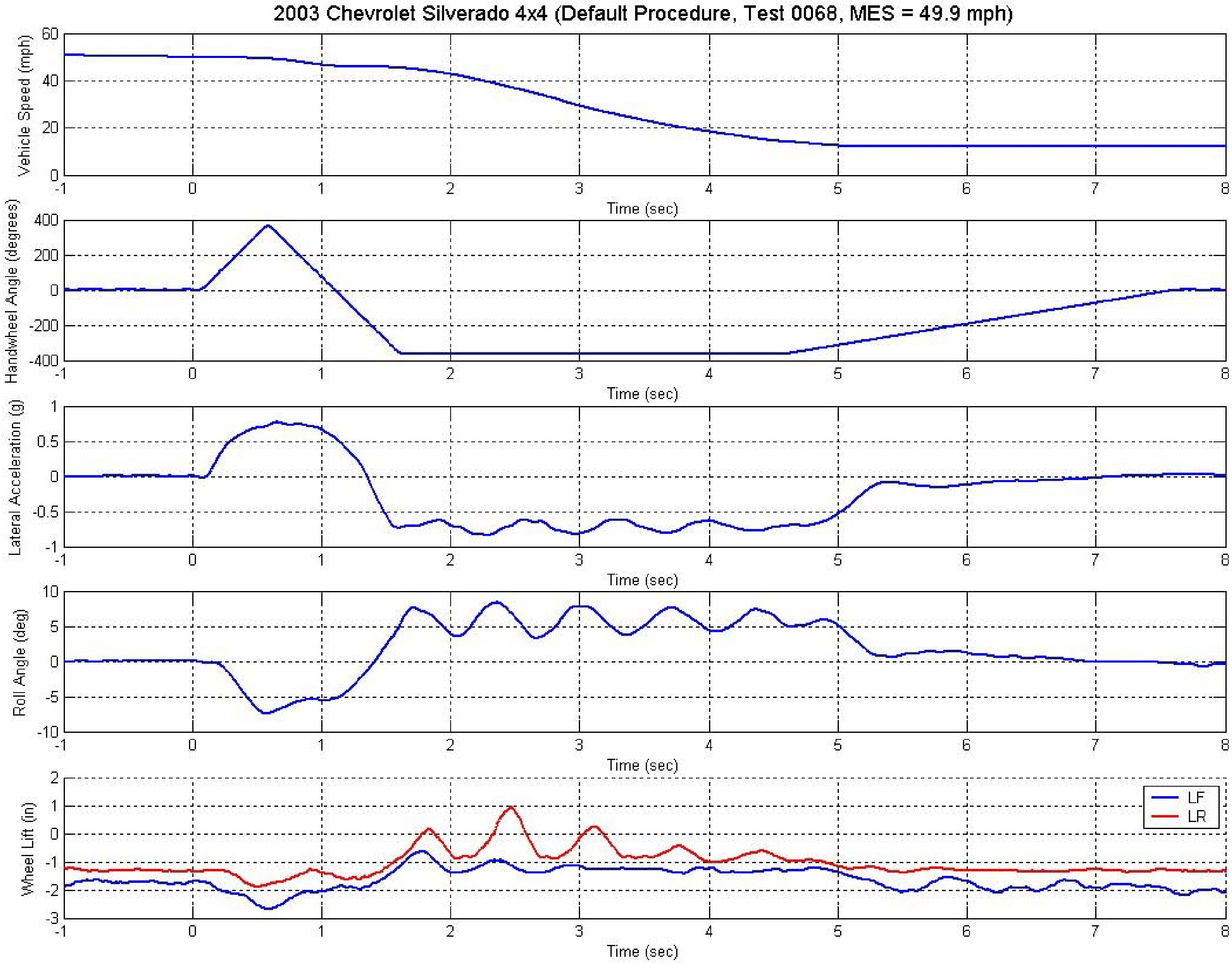

Figure A.39. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Chevrolet Silverado 4x4.

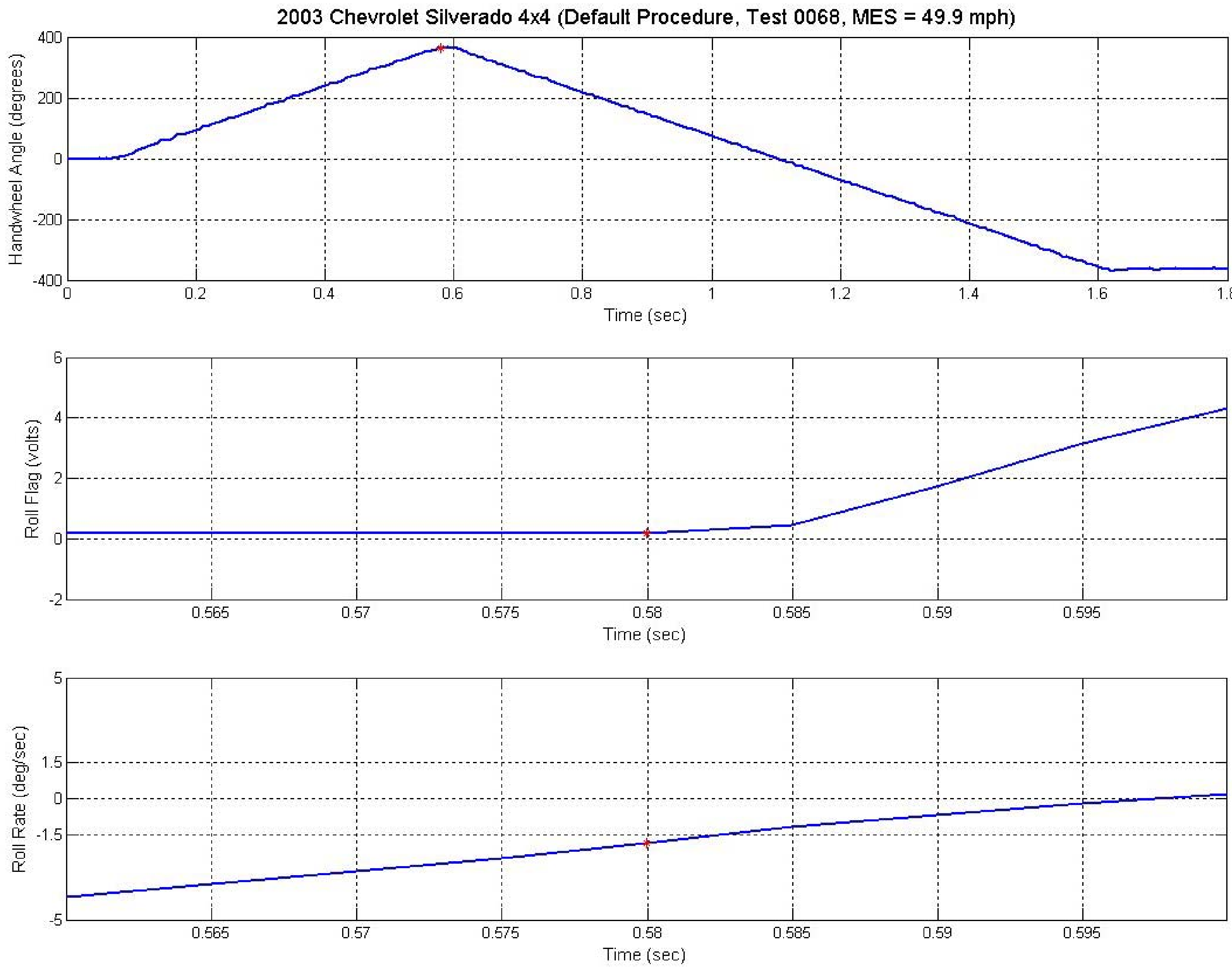

Figure A.40. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Chevrolet Silverado 4x4.

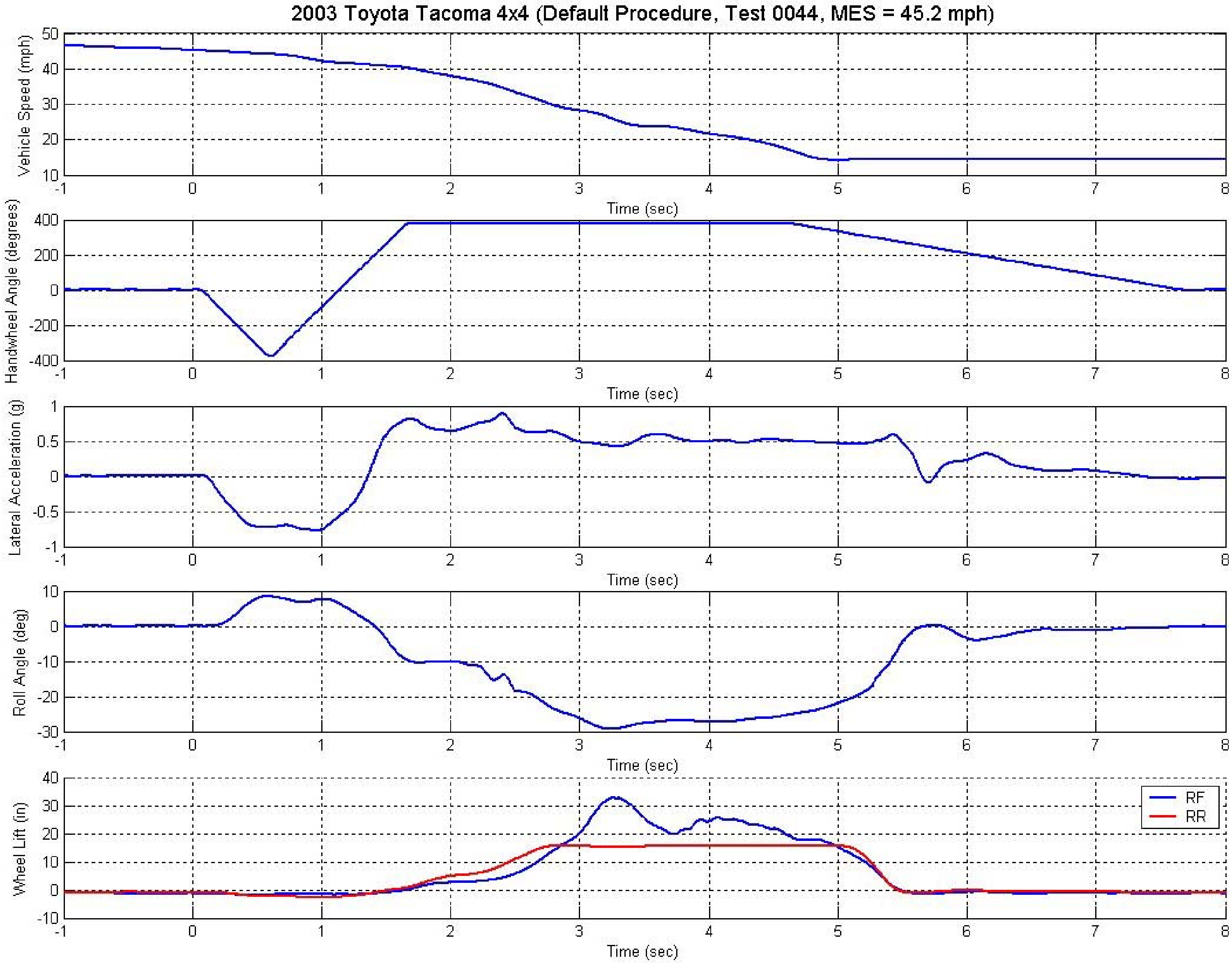

Figure A.41. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Toyota Tacoma 4x4. Note the magnitude of the two-wheel lift.

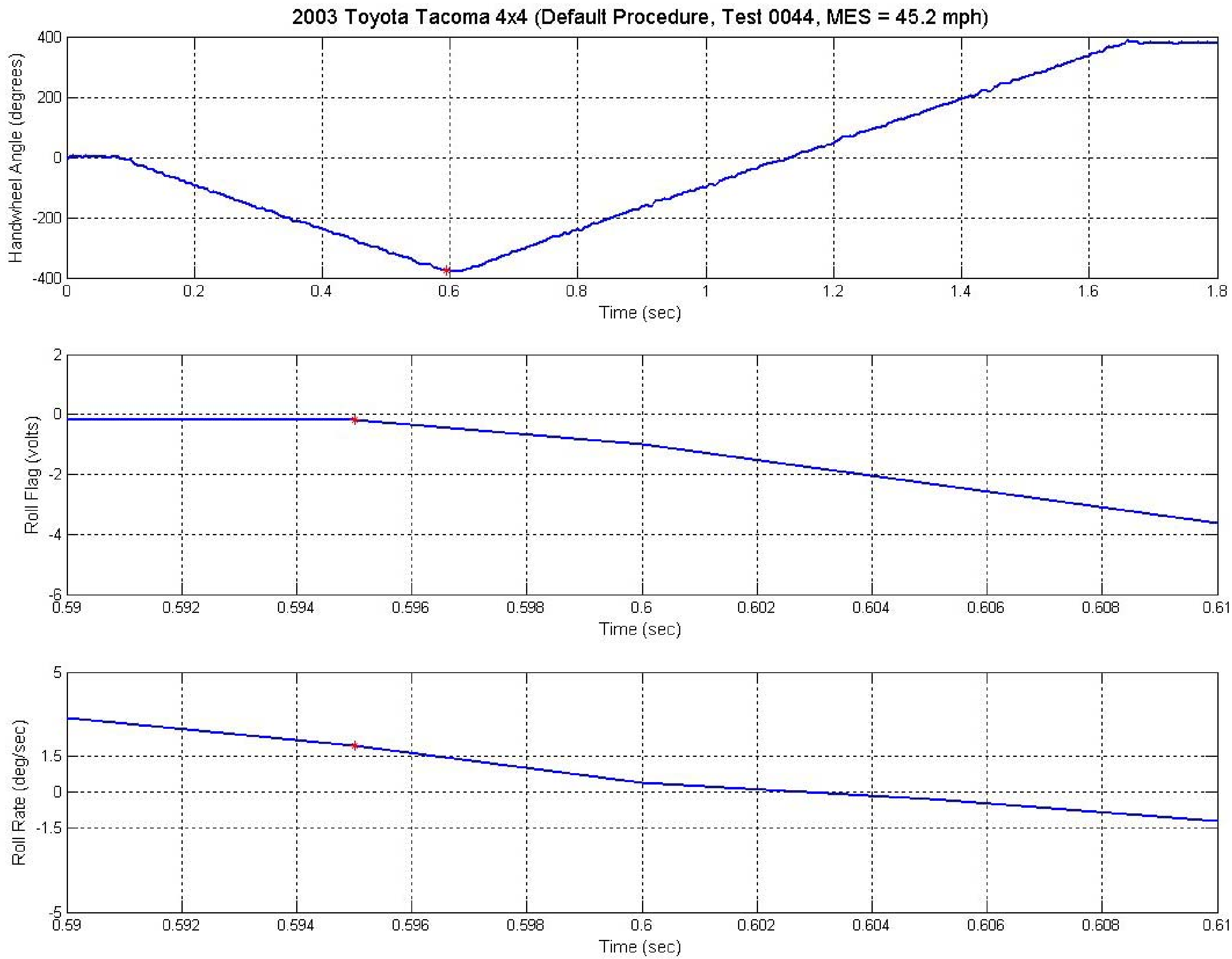

Figure A.42. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Toyota Tacoma 4x4.

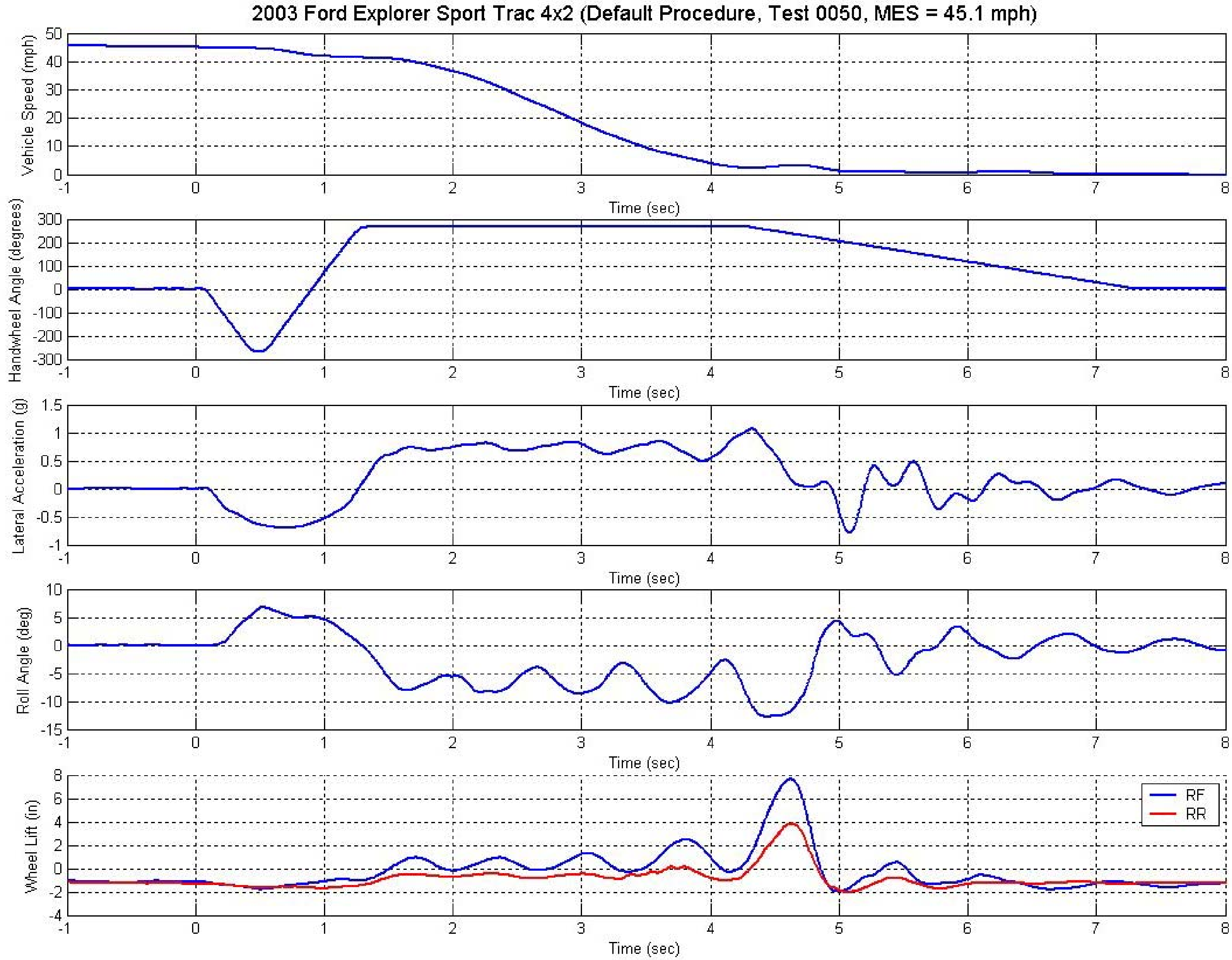

Figure A.43. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Ford Explorer Sport Trac 4x2. Note the magnitude of the two-wheel lift.

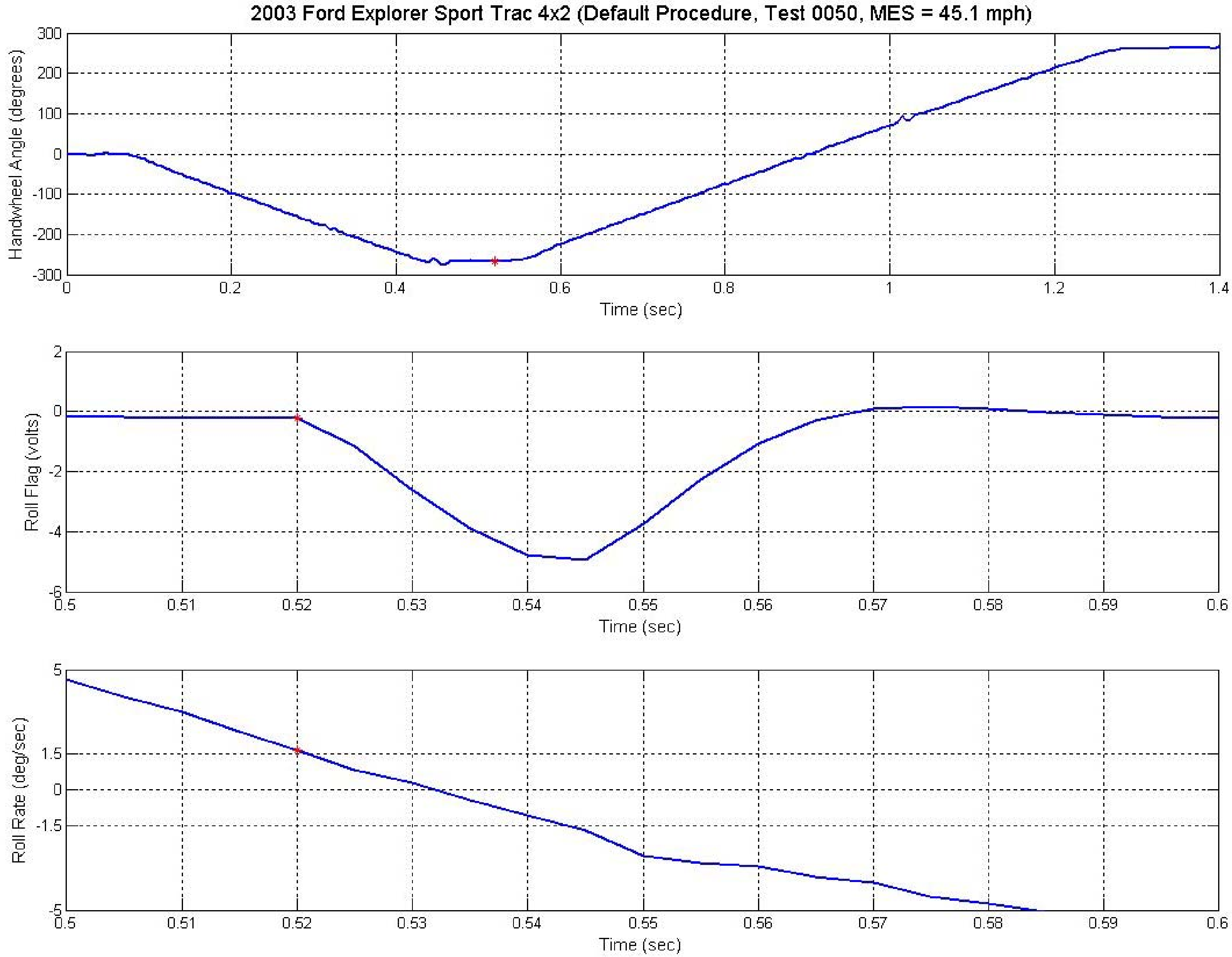

Figure A.44. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Ford Explorer Sport Trac 4x2.

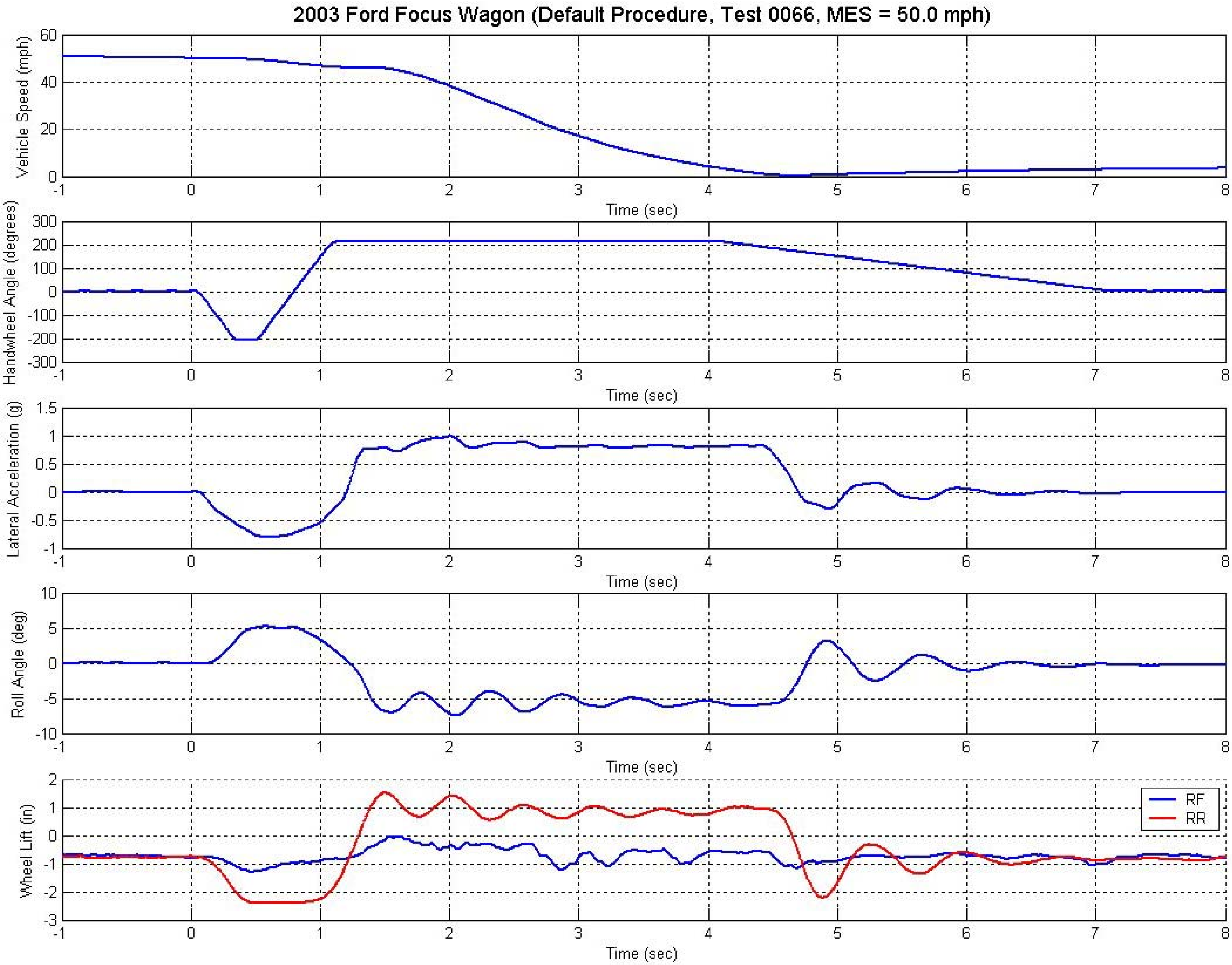

Figure A.45. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Ford Focus Wagon.

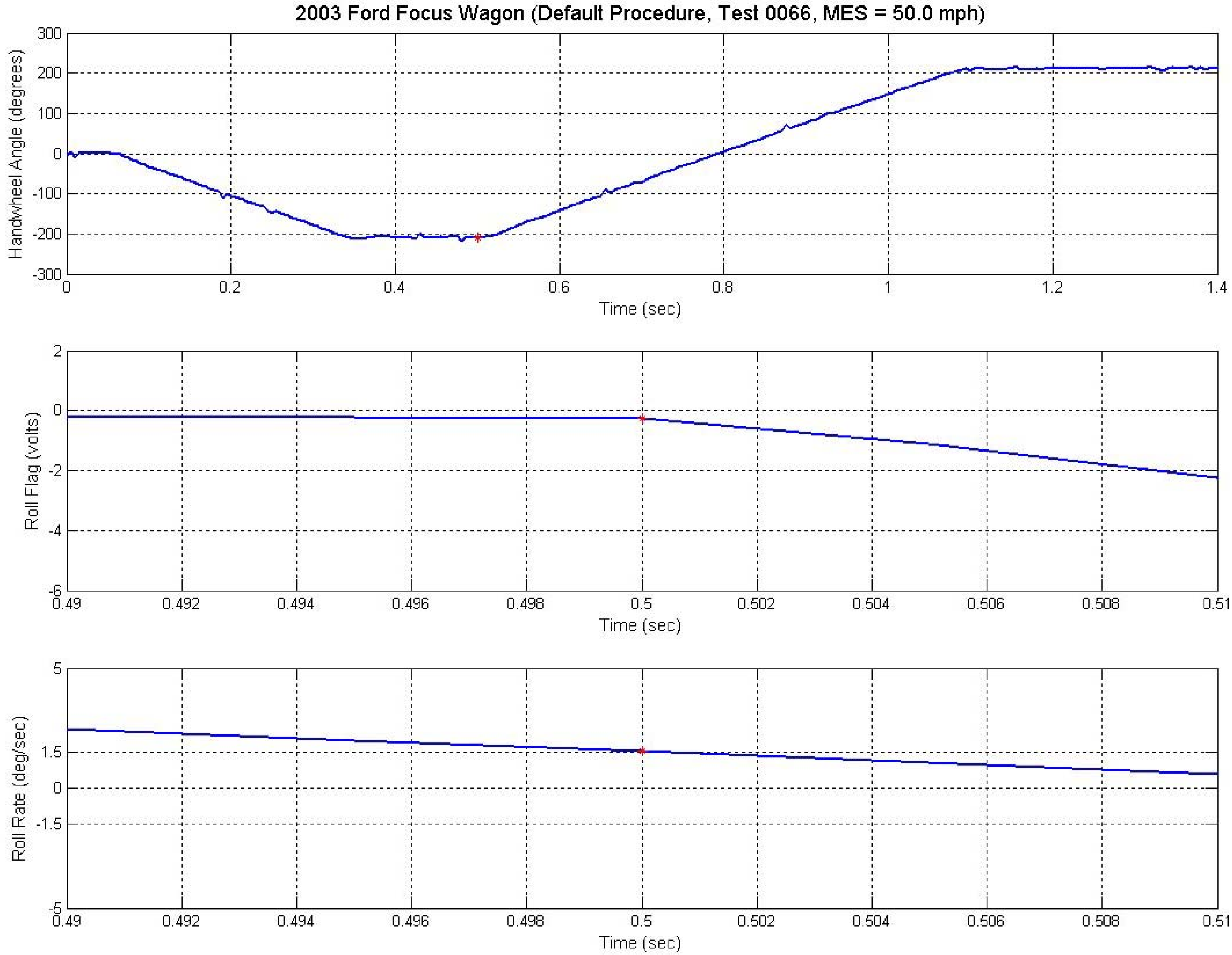

Figure A.46. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Ford Focus Wagon.

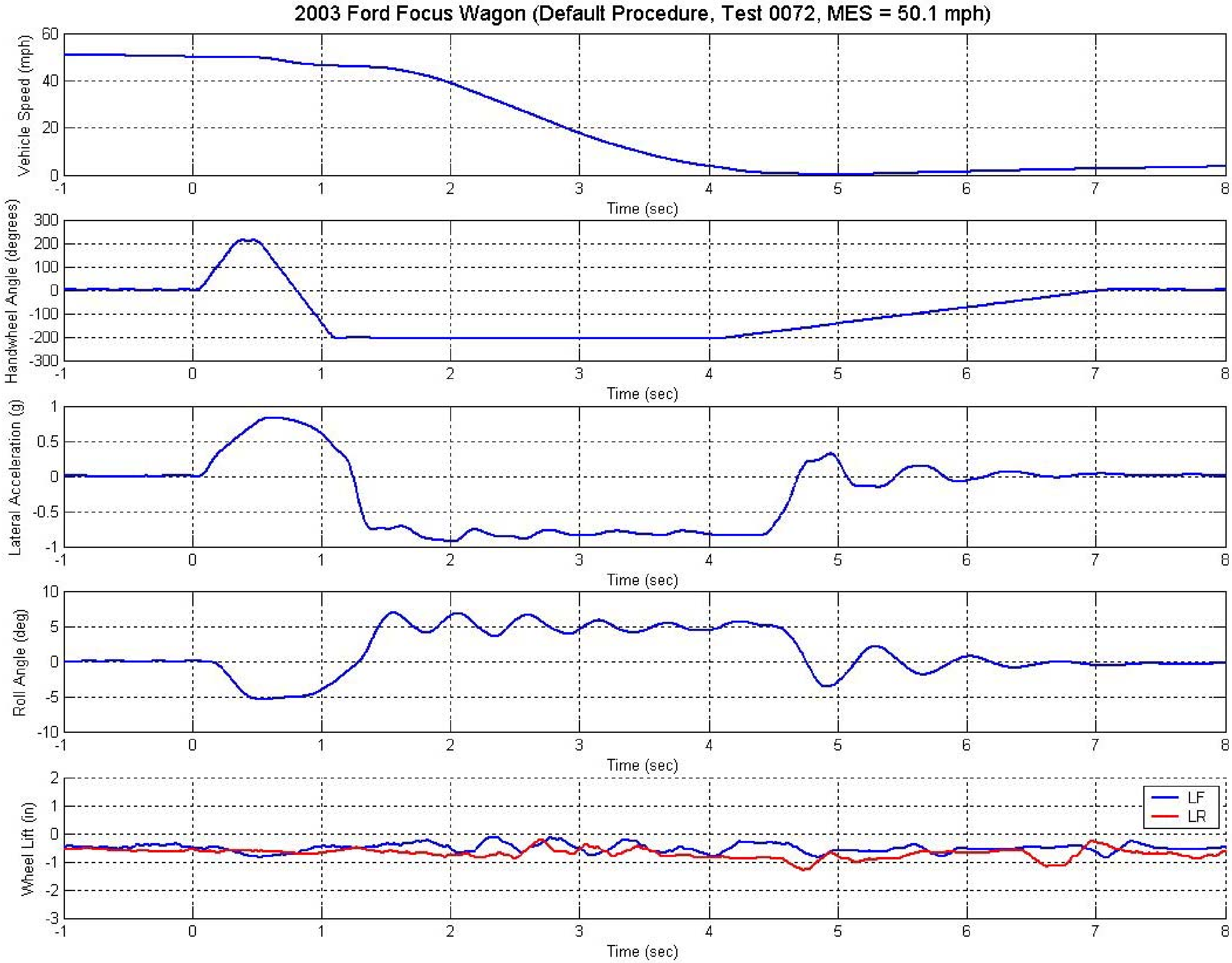

Figure A.47. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Ford Focus Wagon.

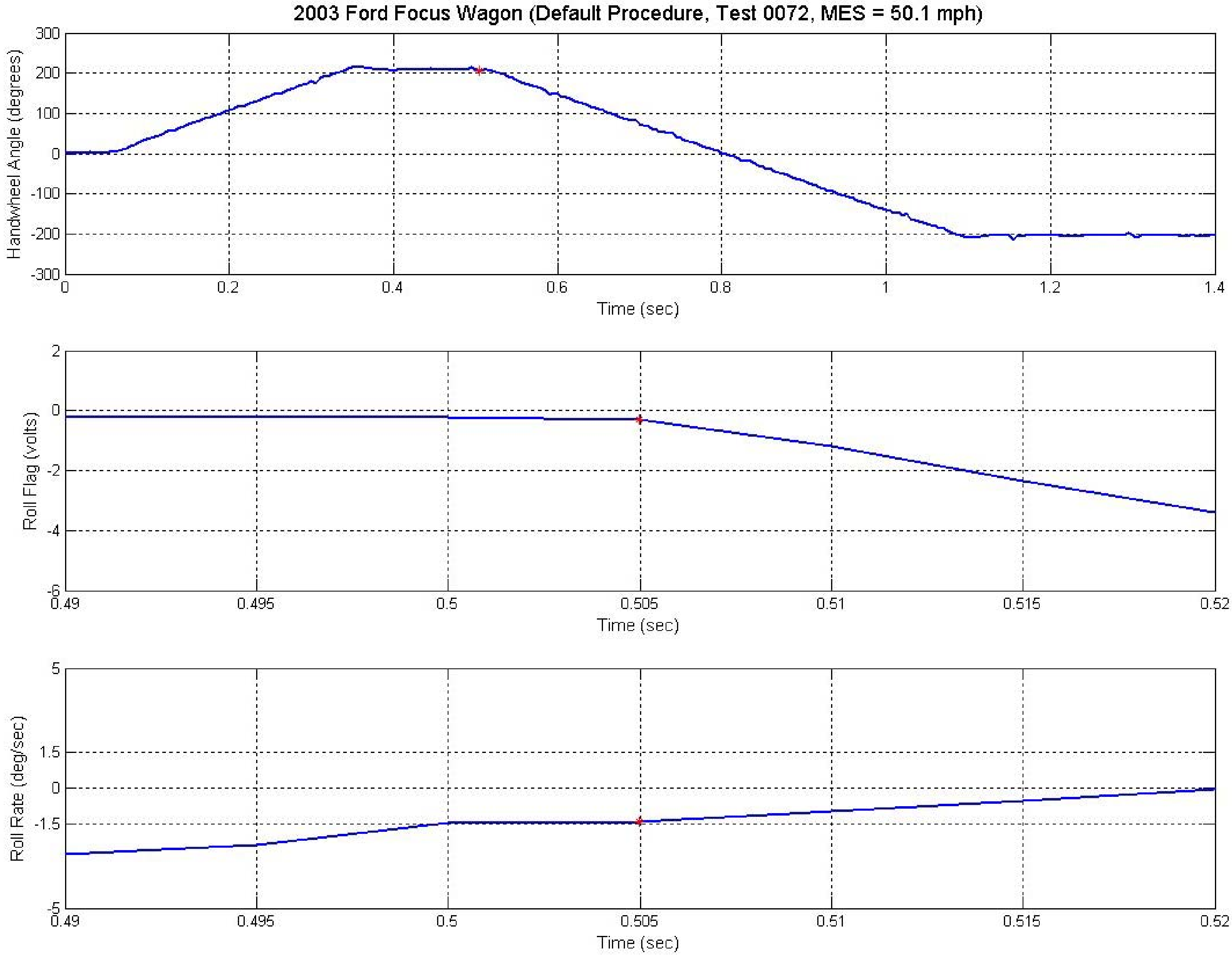

Figure A.48. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Ford Focus Wagon.

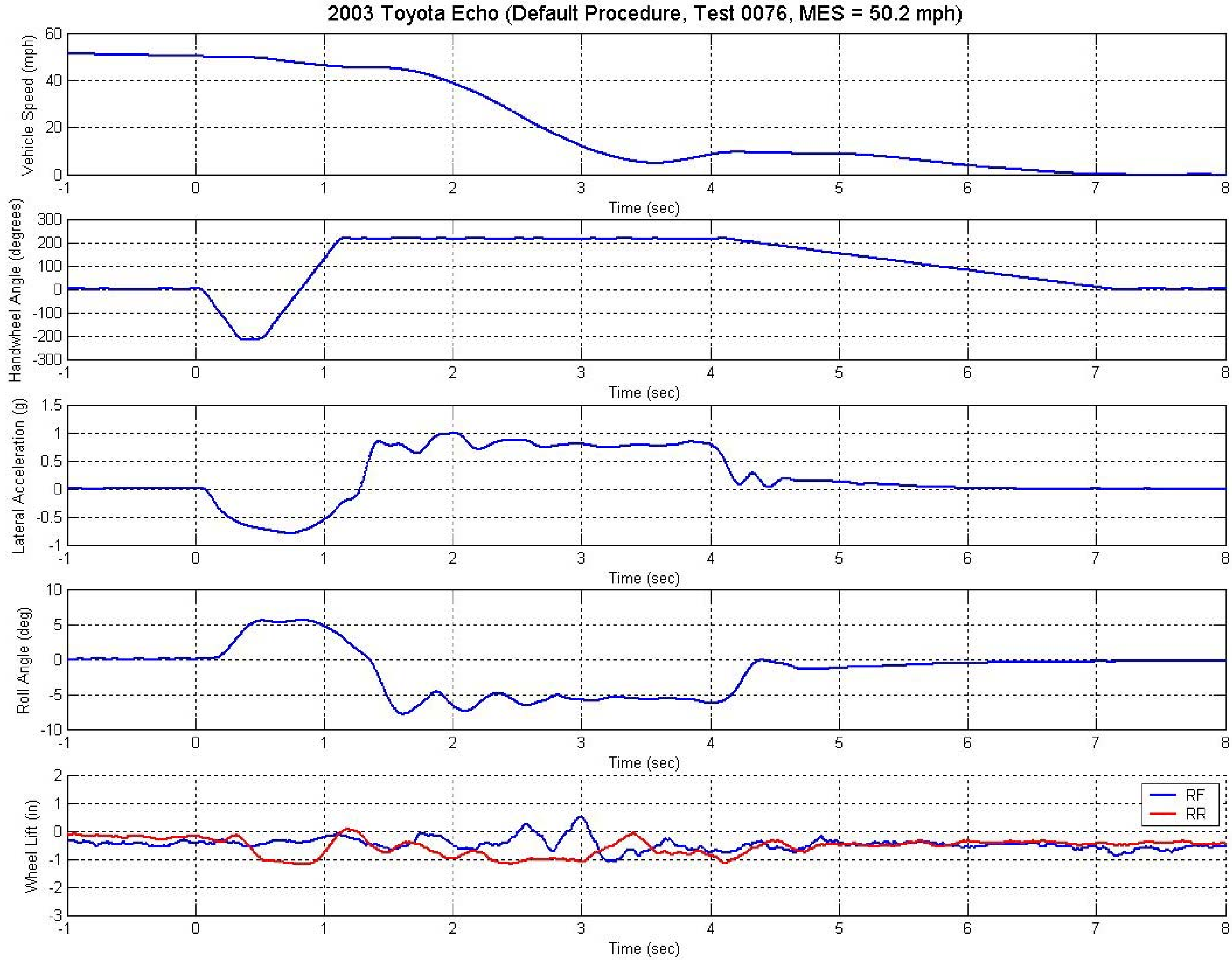

Figure A.49. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Toyota Echo.

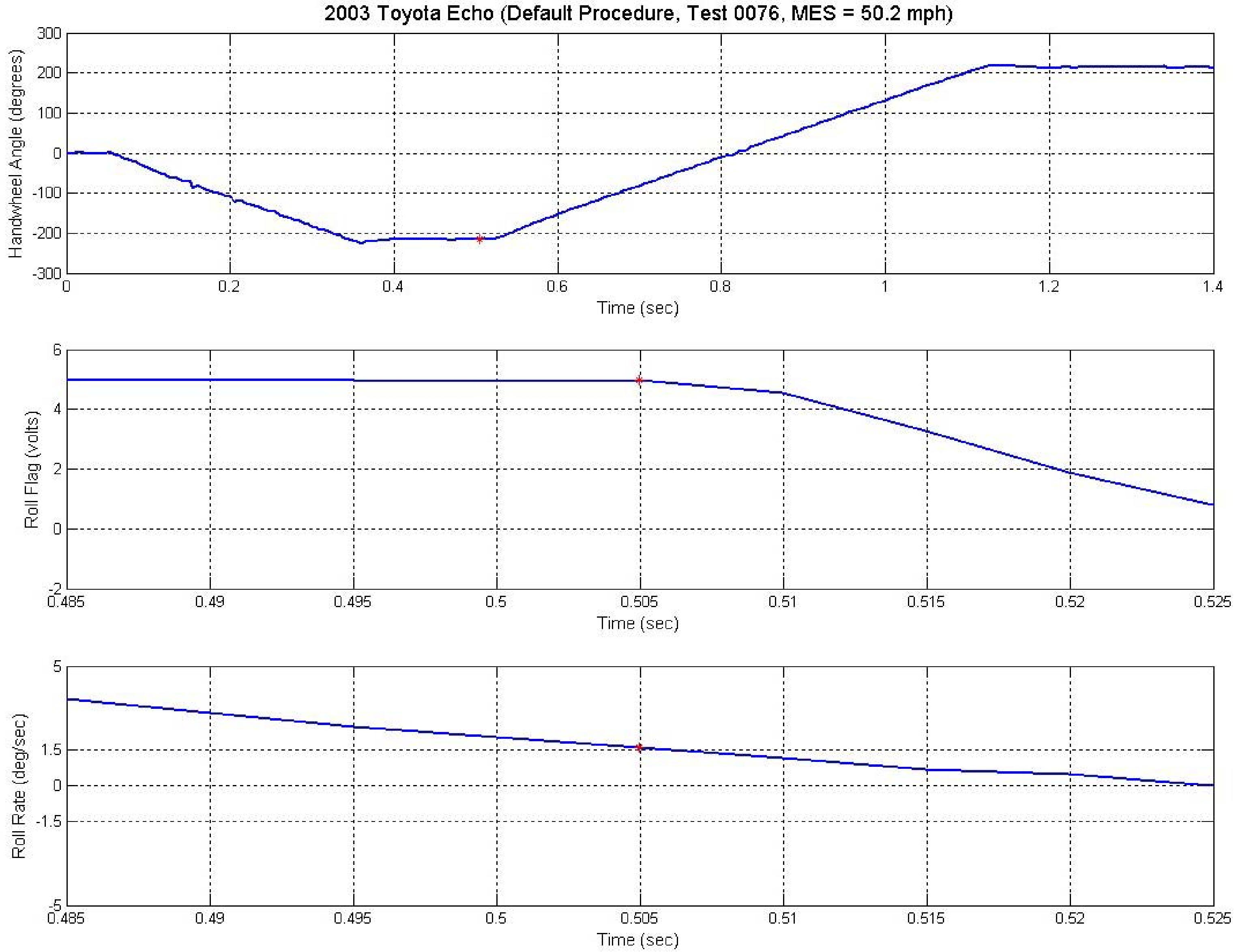

Figure A.50. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Toyota Echo.

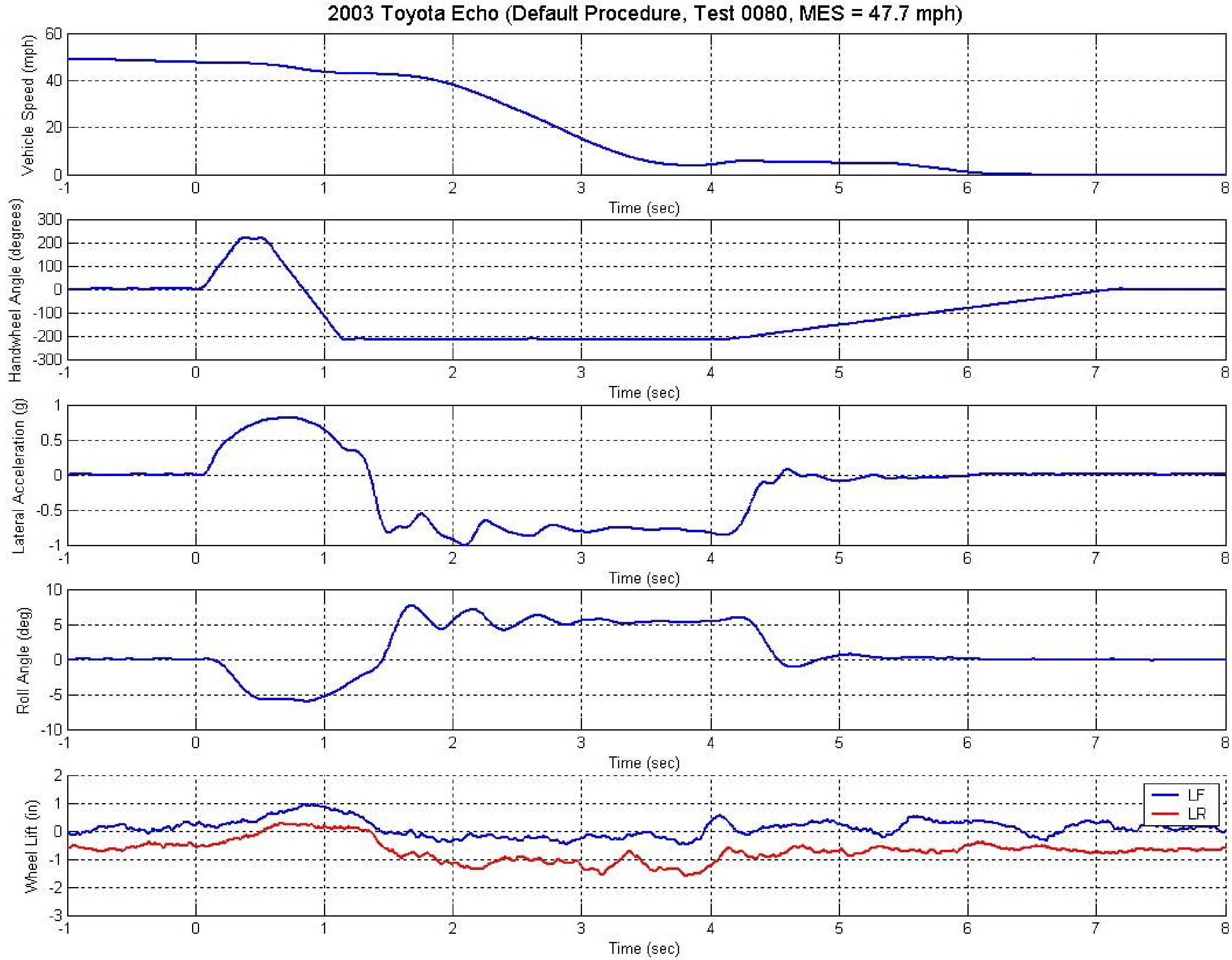

Figure A.51. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a right-left Fishhook maneuver – 2003 Toyota Echo.

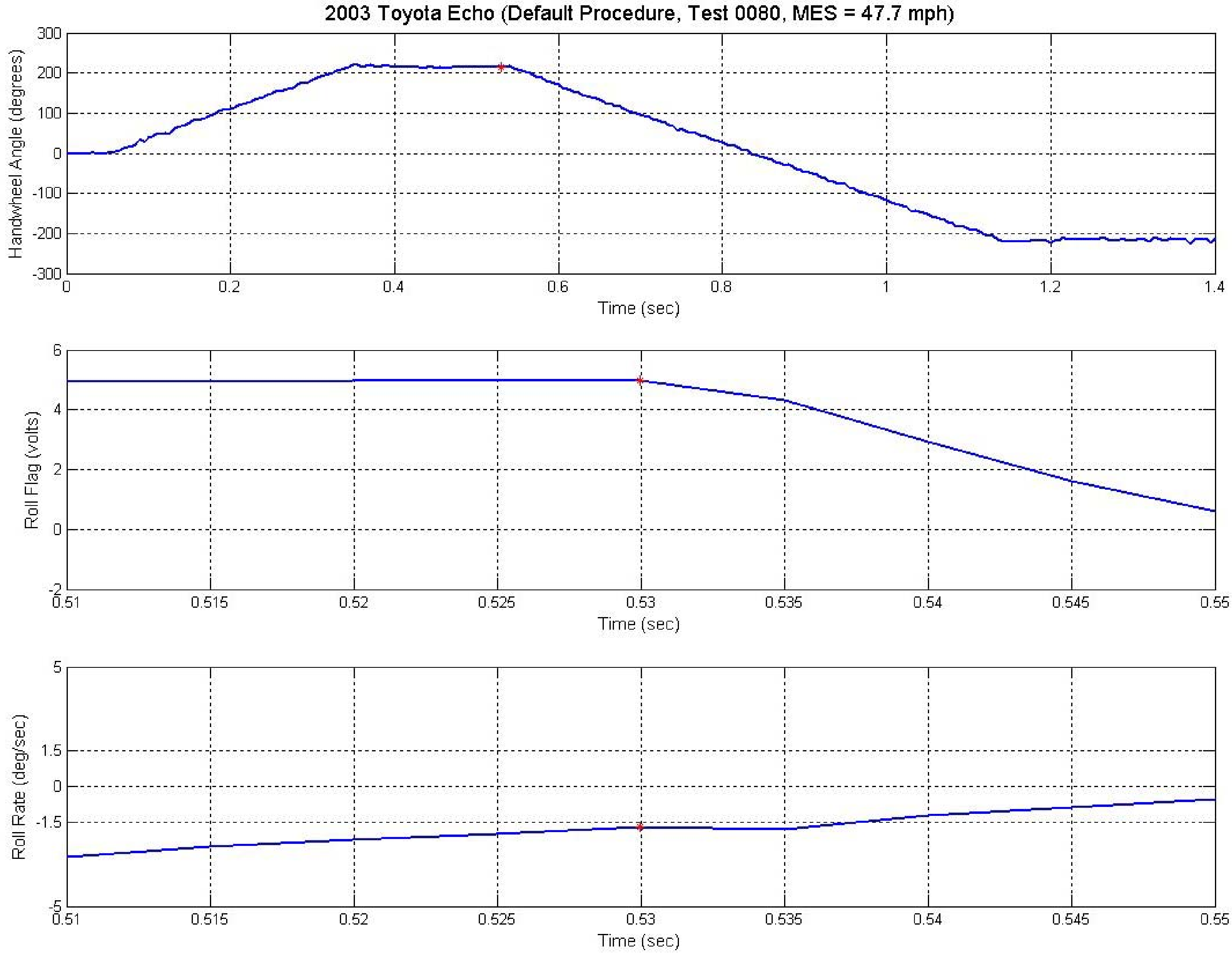

Figure A.52. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Toyota Echo.

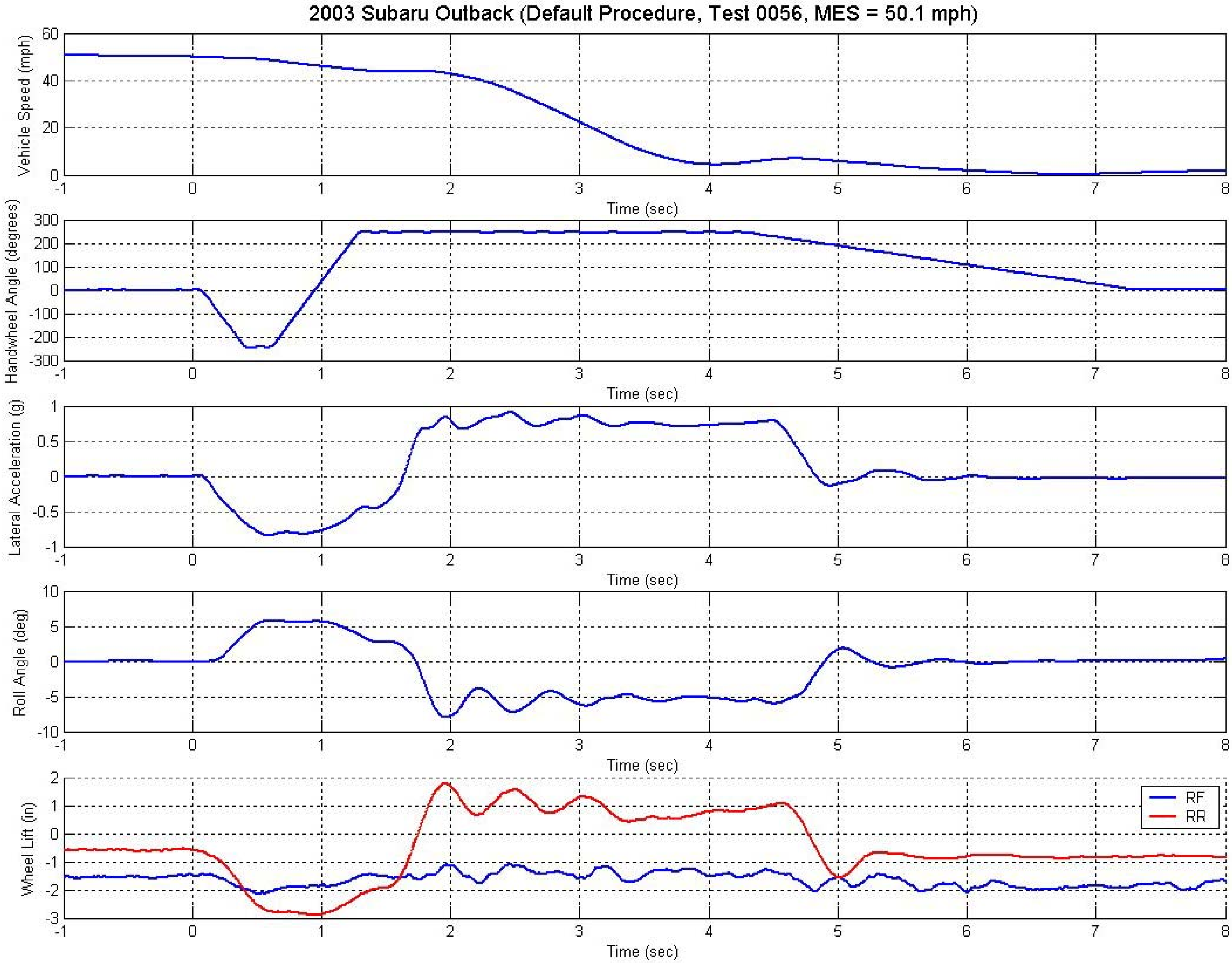

Figure A.53. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Subaru Outback.

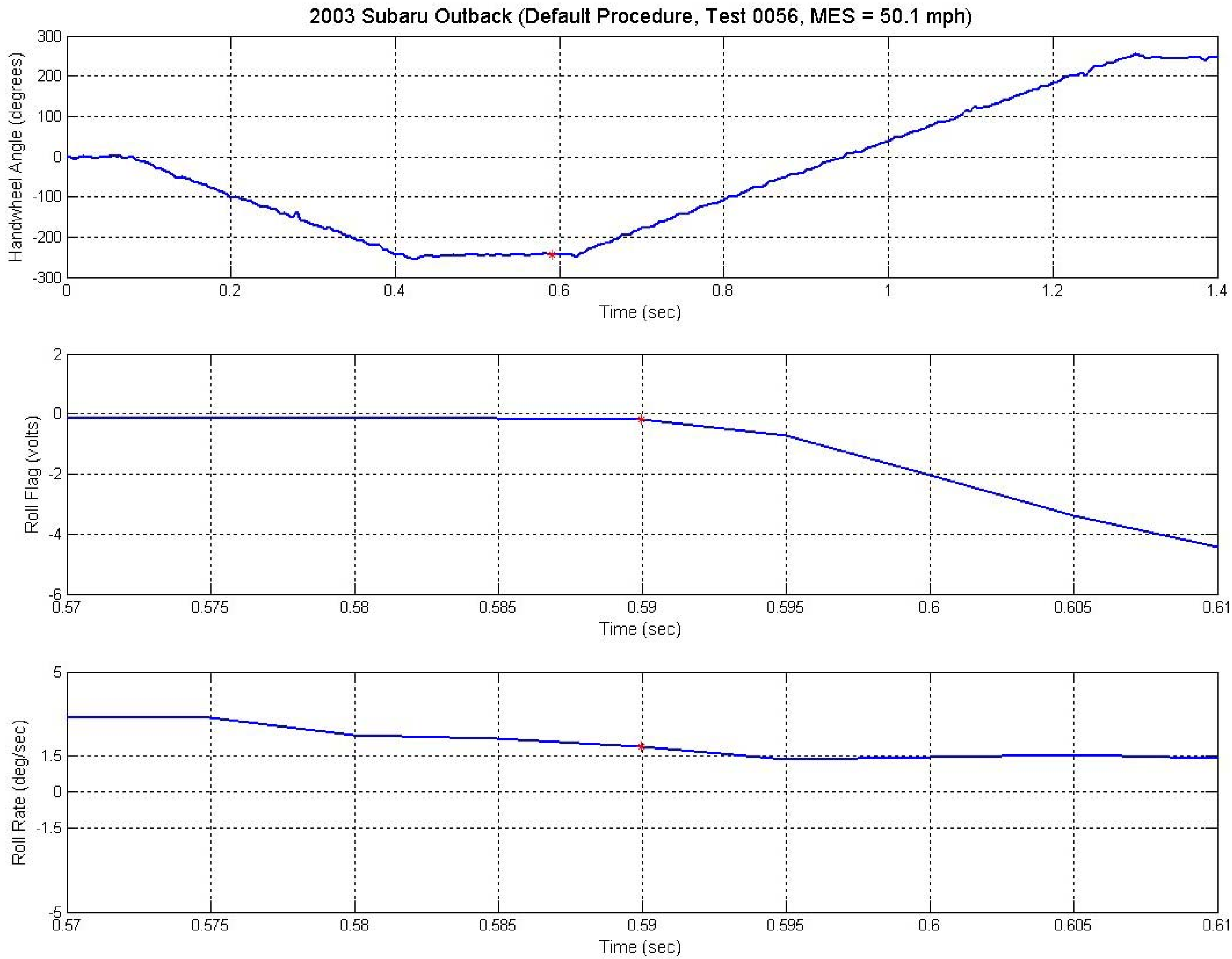

Figure A.54. Steering machine functionality check. Data was collected during a left-right Fishhook maneuver performed with the 2003 Subaru Outback.

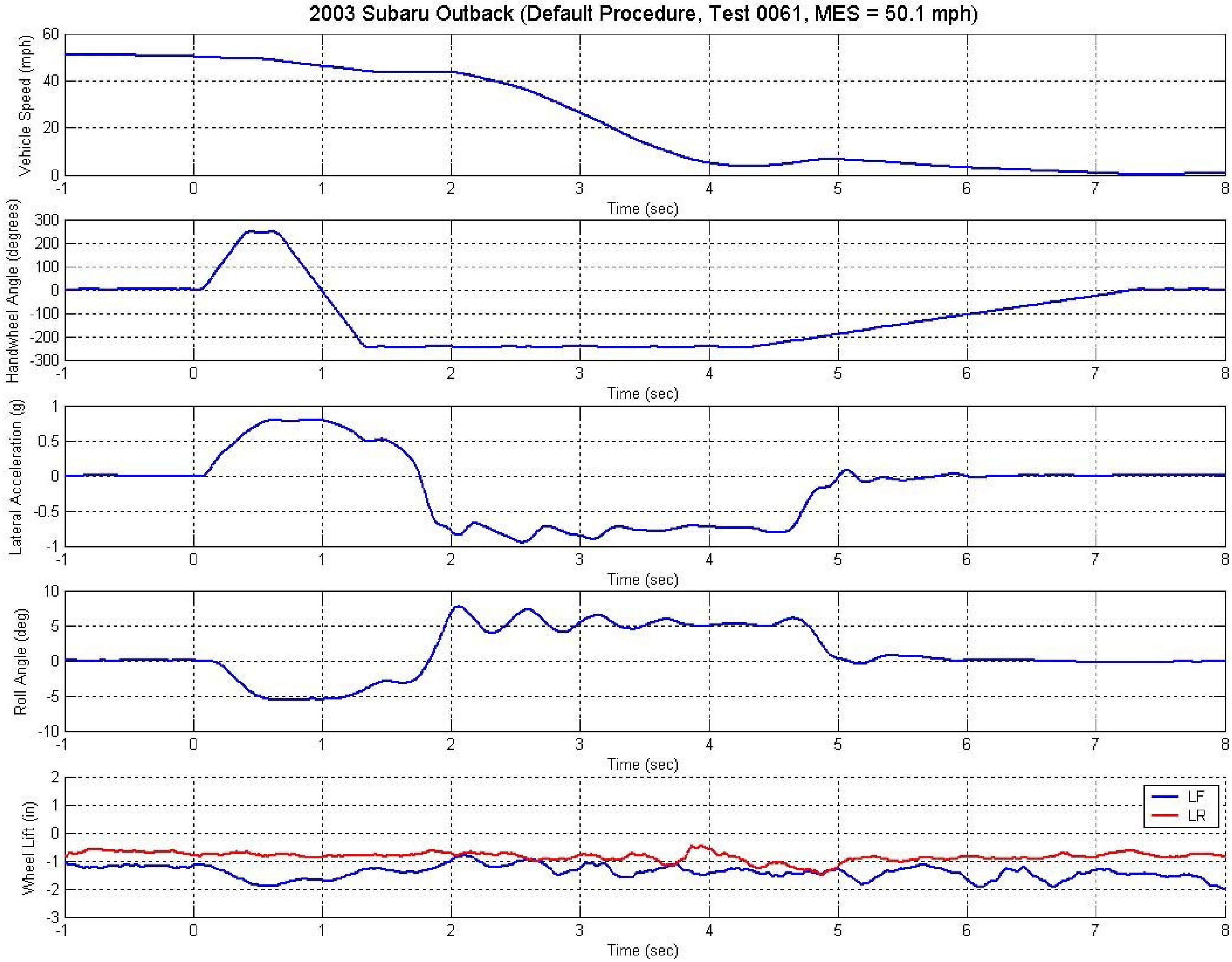

Figure A.55. Vehicle speed, handwheel angle, lateral acceleration, roll angle, and wheel lift observed during a left-right Fishhook maneuver – 2003 Subaru Outback.

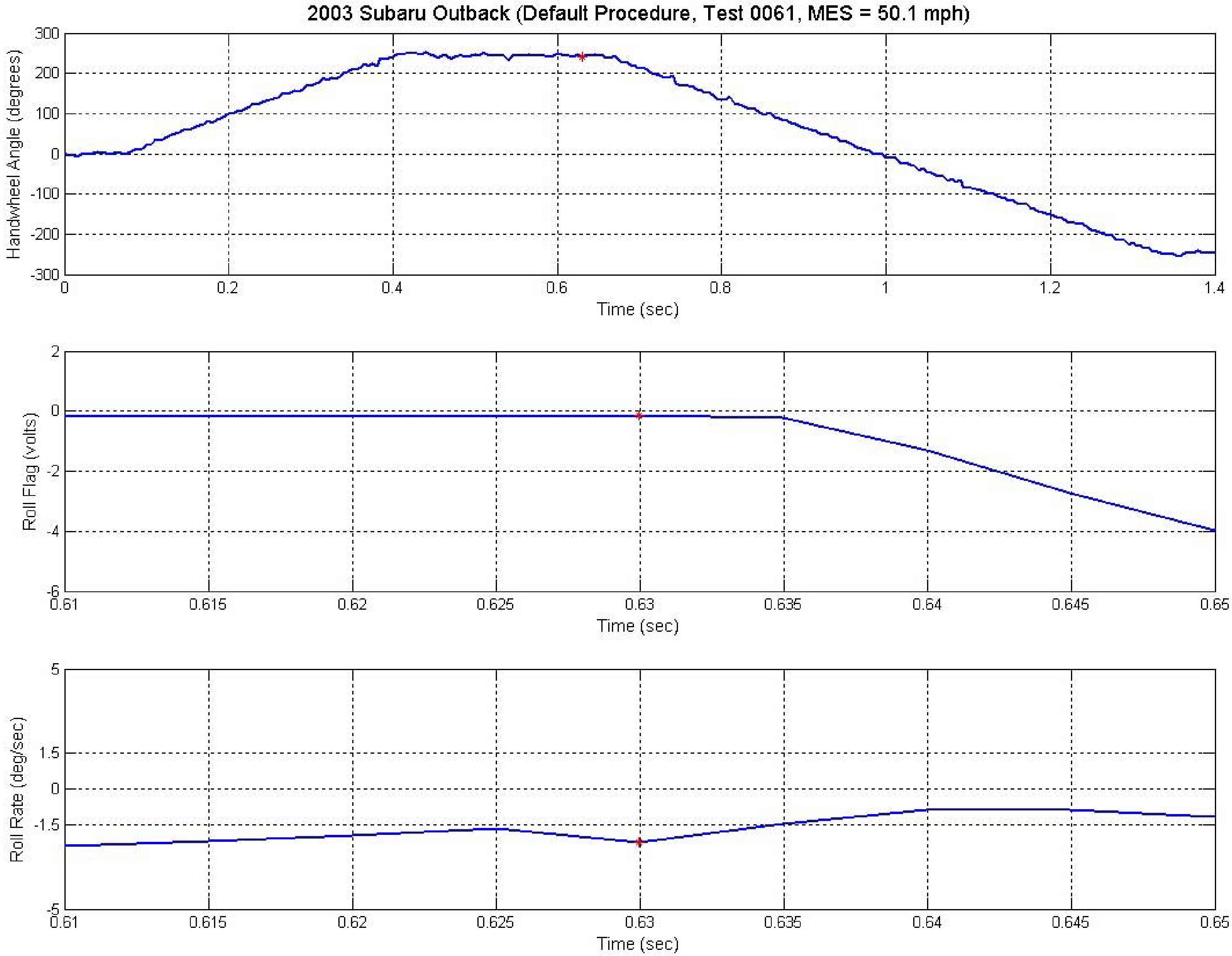

Figure A.56. Steering machine functionality check. Data was collected during a right-left Fishhook maneuver performed with the 2003 Subaru Outback.